UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

INGENIERO EN AUTOMÁTICA Y ELECTRÓNICA
INDUSTRIAL

PROYECTO FIN DE CARRERA

DESIGN OF A CONTROLLED HVAC SYSTEM TO IMPLEMENT IN THERMODYNAMIC AND CONTROLS LABORATORIES.

***AUTOR:* David Morales Galán**

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RESUMEN DEL PROYECTO

Con la ayuda de Siemens Industry, Inc., este proyecto apuesta por la sostenibilidad a través de la implementación de sistemas de control. Una plataforma móvil ha sido construida con el objetivo de contener un sistema de control de calefacción de aire y una interfaz que muestre los parámetros de configuración del controlador implementado y la respuesta del mismo. La Figura 1.1 muestra el diseño de dicha plataforma.

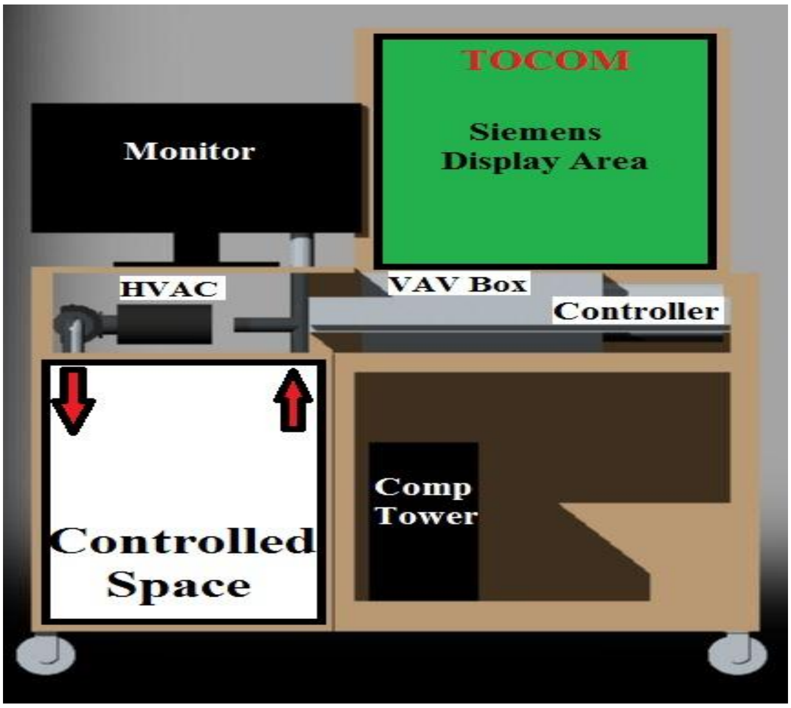

Figura 1.1: Diseño de la plataforma móvil con el sistema de control.

Un pequeño compartimento dentro del dispositivo móvil funcionará como la planta del sistema, en la cual el controlador deberá de regular la temperatura del mismo. El sistema de control de aire introducirá aire caliente o a

temperatura ambiente para calentar o enfriar el compartimento y así alcanzar la temperatura deseada en régimen permanente. El actuador del sistema de control está formado por un ventilador y una resistencia eléctrica cuyo voltaje es regulado por un controlador PID a través de modulación por ancho de pulso (PWM).

Empleando el sistema de control construido y desarrollado, se han diseñado dos guías de laboratorio que serán aplicadas por futuros estudiantes en los laboratorios de termodinámica y de controles de la Universidad de San Diego, donde este proyecto ha sido desarrollado.

Gracias al diseño de una interfaz y la implementación de controles en LabVIEW es posible la obtención de datos en tiempo real y realizar un análisis termodinámico de la eficiencia del sistema en las dos configuraciones diseñadas (con y sin recalentamiento). En la práctica de controles diseñada se podrá variar los parámetros del controlador para ver su efecto en el sistema y comparar los resultados con el modelo no lineal que se ha implementado en Matlab. Un ejemplo se muestra en la Figura 1.2

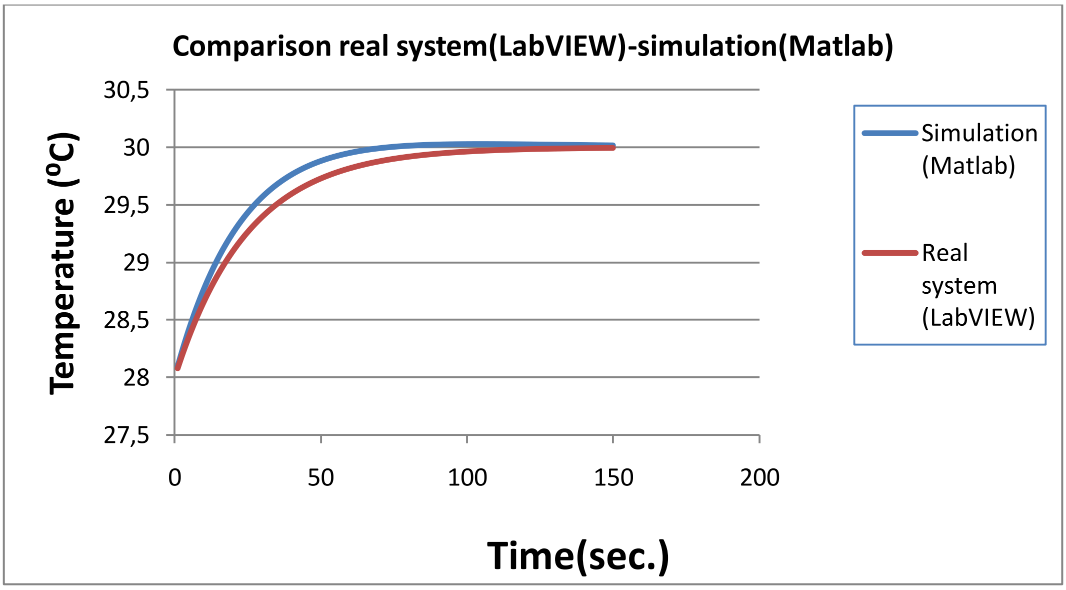

Figura 1.2 Comparación entre la respuesta del modelo real y simulación.

Por otro lado, el dispositivo móvil contiene además una demostración de los sistemas de control de Siemens (Ver Figura 1.1) con la intención de mostrar sus funcionalidades y capacidades. Dicho sistema incluye su propia Interfaz Gráfica (GUI), la cual muestra al usuario de una forma intuitiva y fácil la información de los sensores y demás aparatos de control.

Por último, el dispositivo móvil puede ser transportado fácilmente por la totalidad de las instalaciones del edificio de ingeniería de la Universidad de San Diego con el fin de ser una herramienta útil en las áreas relacionadas con la sostenibilidad.

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ABSTRACT

With the assistance of Siemens Industry, Inc., the TOCOM Lab demonstrates energy sustainability through the implementation of control systems and associated devices in a lab environment. A mobile lab unit was constructed to contain an onboard air control system and display a configuration of control system devices and instruments. The mobile lab unit is shown in Figure 1.1.

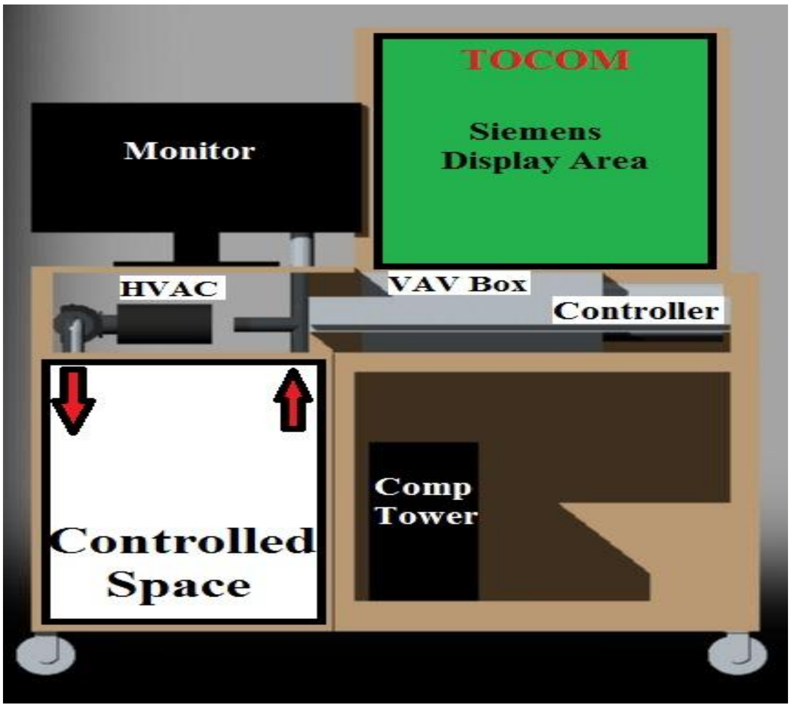

Figure 1.1 Mobile lab unit design.

An enclosed space within the unit serves as a model environment in which a control system will regulate the air temperature. A computer actuated air control system introduces heated or outside air to heat or cool the space to achieve a desired, steady-state temperature. The heating actuator comprises

a fan and a coil whose voltage is regulated by a PID controller through Pulse Width Modulation (PWM).

Using the air control system, both a thermal systems and control systems lab exercise was created with the aim to be applied by future students in thermodynamics and controls labs in the University of San Diego, where the project has been developed.

Real time data collection using LabVIEW allows for the analysis of the thermal efficiency of the system with and without a reheat configuration. The parameters of the control system can also be varied using LabVIEW to provide an instructive exercise in the design of control systems. Furthermore, the results gathered in the real system could be compared with the simulation responses obtained when running the non linear model implemented in Matlab. An example is shown in Figure 1.2.

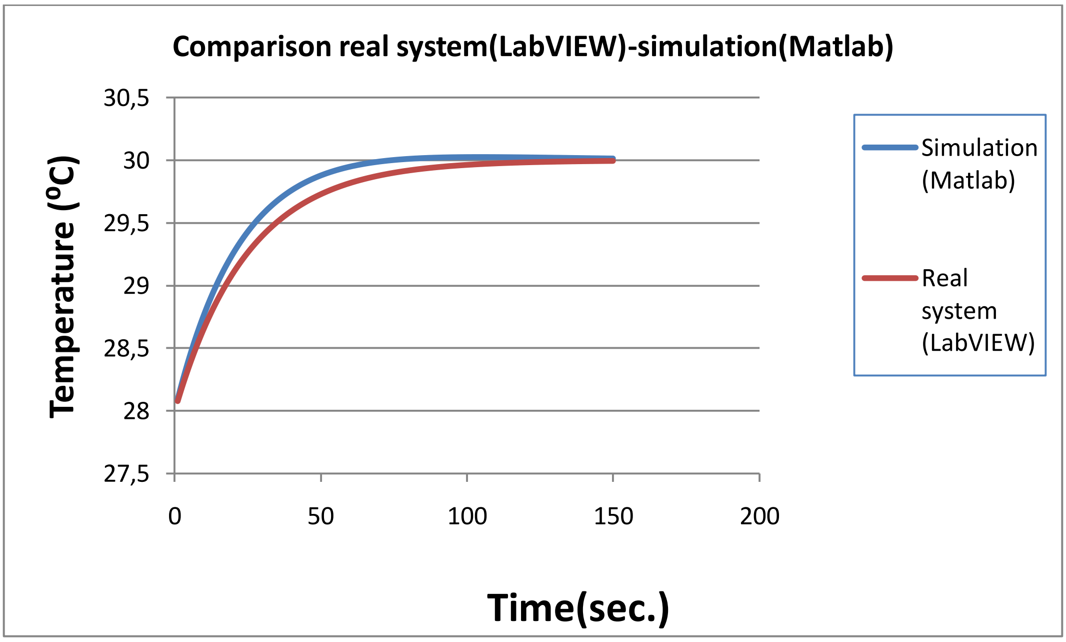

Figure 1.2: Comparison between real system and simulation responses.

The Siemens Control Demonstration provides information on the installation and programming of control devices as well as real time data collection (sensors and control devices) through a graphical user interface. The intention of the demonstration is to illustrate the critical components as well as the capabilities of control systems.

Finally, the mobile lab unit can be transported between the electrical and mechanical engineering labs of the engineering building to provide both departments with a teaching tool for areas critical to energy sustainability.

TOCOM LAB: Design of a controlled HVAV system to implement in thermodynamic and controls laboratories.

University of San Diego

2010-2011 *Department of Engineering*

Final Design Report
May 05, 2011

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PART I

REPORT

Chapter 1

Introduction

1.1 Context

In an effort to encourage continued focus on energy management and sustainability the TOCOM group built a mobile lab unit which demonstrates efficiency and energy management building systems through the implementation of control systems. Working with a leader in energy management, Siemens Industry Inc., the multidisciplinary team had the opportunity to learn how modern building technologies can be used to increase sustainability in operations, and used this knowledge to develop the TOCOM Mobile Lab. The project was divided into two sections: Design and construction of an air control system for a small environment and a demonstration of the Siemens control devices. The air temperature control system regulates the air temperature within an enclosed environment through the use of a miniature heater and fan actuated through LabVIEW. The Siemens control demonstration uses control devices and hardware to show how to program and install real size sensors and display these readings on a Graphical User Interface (GUI).

The two different sections will place their respective parts together on the cart and share a computer that will have Insight and LabVIEW installed on it.

Both groups must be aware of the size of each other's components and to ensure that the display is not only functional but easily accessible.

Air Control System:

An enclosed environment was constructed aboard the cart to contain the air to be conditioned by the control system. The control system and heating, ventilation, and air conditioning (HVAC) system integrated with the enclosed environment will enable the TOCOM mobile lab to be used for both thermal systems and control systems laboratory exercises. The thermal systems laboratory focuses on comparing the system efficiency when air is directly taken from the outside environment or re-circulated within the system. The efficiency can be analyzed through the calculation of heat and power input values based on real time measurements. The control systems lab focuses on the design of control systems using the physical actuators and sensor devices aboard the cart.

Siemens Control Demonstration:

The Siemens control demonstration portion of this project was developed with the help of Siemens Industry Inc.. The Siemens display will feature a Programmable Controller (PXC) that is the main processor for all information generated in the Siemens lab. On the cart, a group of sensors for Temperature, Humidity, and carbon dioxide (CO2) are to be placed on a display panel so that they can be easily seen. On the display panel there is also a Fire Alarm Pull Switch, Fire Strobe Light, and a Terminal Equipment Controller (TEC). Placed below this panel is a Variable Air Volume (VAV) box with an attached Actuating Terminal Equipment Controller (ATEC) that will turn the damper in the VAV box along with measuring pressure drops. This information is sent to the PXC through the Floor Level Network (FLN) and

the readings from the other sensors and buttons are wired directly into the PXC.

All of the previously stated information is to be displayed on the GUI. The GUI is placed on the main computer also located on the cart. The GUI is to be easily accessible and user friendly while also allowing a user to learn about the system's design.

1.2 Problem definition.

The problem that this project is attempting to solve is to successfully implement a mobile lab with an onboard controlled environment to propagate knowledge critical to energy management and sustainability. The mobile lab must facilitate its own transportation within the confines of the engineering labs in Loma Hall. The lab, which caters to more advanced users in the form of control systems and thermal systems labs, must also be able to serve as teaching tool for the basics of control systems and associated devices for any person who interfaces with the lab. University of San Diego (USD) is increasing its sustainability campus wide; demonstrating energy sustainability with an engineering controls lab will serve as yet another example of its efforts to increase sustainability.

1.2.1 Customer Requirements

The customers for this project, USD students, faculty, and staff, require a mobile lab that has the following characteristics:

1. Measurements of the surrounding environment, including temperature, humidity, and CO2 content of the air displayed on a GUI running on an onboard computer

2. All components need to be visible and clearly identified to users, interacting with the unit
3. Safe mobile lab unit for future use by USD students, faculty, and staff
4. Laboratory exercises which can be performed in both thermal science and control systems engineering using the mobile lab
5. An easily navigable GUI conveying information concerning control system devices

Physical Requirements

The mobile cart unit will present unobstructed visual of air handling equipment, control devices, and other sensors. All components need to be physically supported as well.

Since the mobile cart will be used as a teaching tool in different labs, it must be mobile and able to fit in engineering labs and the elevator.

An onboard computer must be supported physically and electronically

Functional Requirements

TOCOM's mobile cart must fulfill the following requirements:

- GUI allows user to interface with control system devices.
- Confined space must be able to maintain a prescribed temperature at steady state.
- Construction and implementation costs less than projected budget.
- Readings for temperature, CO_2, and humidity displayed for public access.
- Entire control system can be displayed to users.

- The GUI, LabVIEW, and both the thermal and control systems lab exercises need to be stored on the computer that can be used by a person standing up or seated on an elevated lab chair

1.2.2 Assumptions

The design has been constructed based on the following assumptions:

- The TOCOM Mobile Lab will be used within in the engineering labs.
- Siemens will provide the team with the suitable components in accordance with a budget.
- The lab cart will have access to a power supply whenever it is to be used

1.2.3 Constraints

On the one hand, laboratory must conform to safety protocols for electrical and mechanical safety, so users will be protected from moving parts, sources of heat, and electrically isolated from dangerous components such as wires or transformers.

On the other hand, laboratory and components must be contained on the mobile cart to make it easier to use and move.

Finally, components concerned with the Siemens Control Demonstration must be obtained from Siemens and their software Insight must be used as well.

Chapter 2

Design specifications

Before going into details about contruction, programming and implementation, this chapter has the aim to explain the specifications that the different subsystems have to fulfill. Setting the specifications is really important to understand the different subsystems involved in the project, meet the requirements and come up with a suitable design.

2.1 Design overview

As it has been mentioned before, the project is basically composed by two sections whose overall design is going to be described next.

Air Control System

The footprint of the constructed laboratory is 4 feet in length and 25 inches in width to facilitate transportation throughout the enginnering building. The most important goal of this lab design is that it be able to maintain a controlled environment while at the same time being able to demonstrate the energy efficiency capable through the use of control systems. The control system maintains the environment by intermittently hot air or pumping fresh air to achieve a steady-state temperature.

Siemens Control Demonstration

To convey the basics of control systems and their associated devices, the lab is be outfitted with a series of sensors for temperature, humidity, and CO2. The lab is also equipped with a VAV box which demonstrates how the controlled environments in building systems are regulated.

2.2 Functional specifications

Primary functions of the project are related to the user interaction with laboratory exercises and the Siemens Control Demonstration. Users must be able to activate all components via the onboard computer or switch related to the demonstration. Descriptions of the projects functional specifications are explained in more detail below.

A. Maintain Temperature

- Temperature sensor reads actual temperature within a range supporting the lab exercises.
- A fan and heating coil add a heated volume flow rate to the enclosed environment.
- The virtual control system, run in LabVIEW, interfaces with the physical system via a DAQ (Data AcQuisition device).

B. Provide Exercise in Thermal Efficiency Analysis

- The thermal systems lab provides an opportunity to analyze and compare efficiency of different thermal systems.
- Onboard data collection facilitating the calculation of efficiency.
- Variable system configuration allowing for comparison of similar systems with and without recirculation of conditioned air.

C. Provide Exercise in Control Systems Engineering

- The control system of the enclosed environment can be changed in accordance with user input.
- The lab shows how variation Proportional-Integral-Derivative (PID) controller parameters will change how the system response to a desired input.
- The lab will be equipped to show how a non-linear system can be converted to a linear system and the results will be displayed.

D. Display Values of Sensors

- The sensors on the lab provide real time measurements to the GUI.
- The control devices provide responses to user inputs to the switches installed on the cart.
- The controller is programmed to run specific routines if specific inputs are detected.

2.3 Physical specifications

The TOCOM Lab was required to be mobile, allowing for the transportation of the cart between different labs in engineering's building implying it would be able to fit through doors and on the elevator. The TOCOM Lab was built aboard a cart which has a footprint of roughly 4ft by 2ft and a maximum height of 64 inches. The cart is mounted on 4 swivel wheels which facilitate positioning within the labs. The TOCOM Mobile Cart supports the onboard subsystems by providing each with adequate space while allowing for user interaction with the onboard computer system.

The HVAC system was designed to house and insulate a heat source and fan. The circuit is constructed of both Acrylonitrile Butadiene Styrene (ABS) and PolyVinyl Chloride (PVC) plastic tubing. The inlet and exhaust to the enclosed environment are both 1 inch in diameter. The heater and fan housings are each 3 inches in diameter with variable diameter steps interfacing the two different tube sizes. The HVAC system safely provides the heated air necessary for the lab exercises.

Chapter 3

Design analysis and results

Once the specifications have been set, this chapter tries to give a technical description of the design process for each subsytem. First, a general description of the main systems (Air control system and Siemens demonstration) will be presented before going through the different subsystems that comprise the project.

With regards to the HVAC system implemented, the small scale model of a real air temperature control system is composed of the enclosed environment and the HVAC loop. The valve actuators, fan motor, and electric resistive heating coil within the HVAC loop are activated and controlled by relays thrown by the control system. Operated through a computer with LabVIEW and interfaced to the HVAC loop through a data acquisition device (DAQ), the control system actuates the devices to control the air temperature in the enclosed environment. The control system compares the measured temperature to a user specified temperature and responds by adding heated or cool air to the enclosed environment. The block diagram for the HVAC Demonstration is shown below in Figure 3.1.

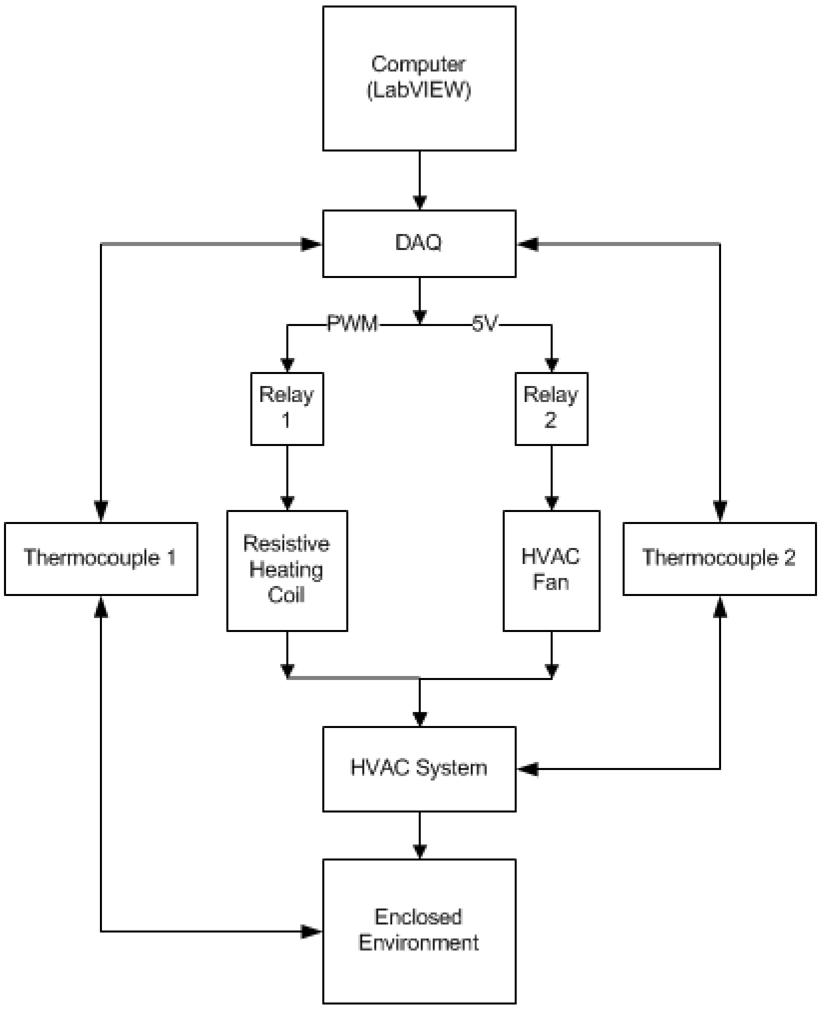


Figure 3.1: Block diagram for air control system

The Siemens display is composed of a PXC Controller that is connected to a group of sensors that send their respective results back to the controller for analysis. In addition to the sensors a Fire Alarm Pull Switch is connected to the controller which turns a Fire Strobe Light on when pulled. All of these values along with an explanation for the system's design are placed in a GUI

which is easily accessible and readable to the user. The block diagram for the Siemens display is shown in Figure 3.2.

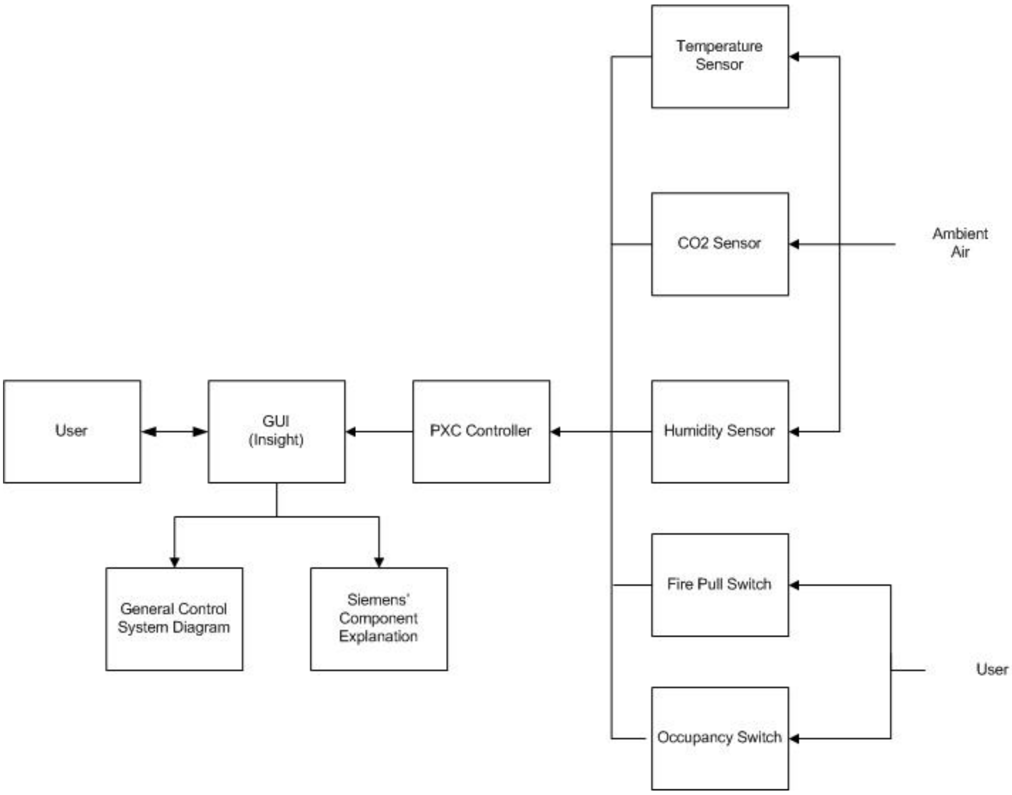


Figure 3.2 Block diagram for siemes display

A system layout diagram is shown in Figures 3.3 and 3.4 for the overall system.

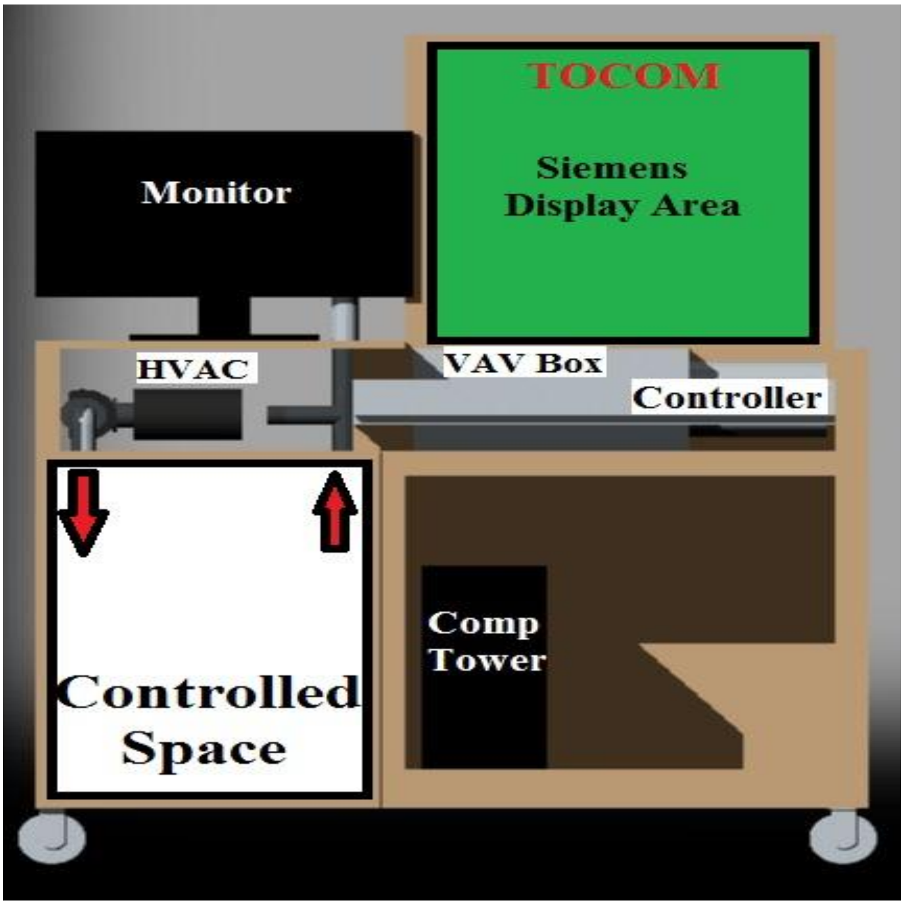


Figure 3.3 Overall system layout diagram.

Figure 3.4 Picture of actual display

3.1 TOCOM mobile cart and thermal systems lab

The mobile cart with onboard enclosed environment meets the specifications as shown in Table 3.1.

Specifications	Design
Enclosed environment enabling temperature control	Sealed box made of wood with door to facilitate sensor access
Portable lab unit to be used throughout Loma Hall	Cart on wheels supports onboard subsystems, dimensions within elevator and door constraints
Stores and provides space for onboard computer used for control of subsystems	Space provided for computer tower, monitor, DAQ, and other components aboard cart
Provides space for onboard HVAC and air-recycling loop	HVAC loop installed and functioning onboard cart
Provides space for demonstration of Siemens components	Backboard constructed on cart for placement of components and concealment of wires

Table 3.1 Design description for mobile cart with enclosed environment

The cart is currently constructed to meet the specifications described above. The cart meets all functional requirements; the accommodation of other subsystems is described in the testing section (Chapter 4). The dimensions and further documentation can be found in the plans attached.

By following the lab procedure (found in Appendix, Chapter 2), students can investigate and compare the efficiency of an air temperature control system to a similar system utilizing an air recirculation loop. The thermal systems lab meets the required specifications, as seen in Table 3.2.

Specifications	Design
Thermal systems lab will enable students to compare power savings due to recycling loop.	Lab handout directs students to measure and compare efficiency for HVAC operation with and without the recycling loop.
Temperature readings before and after addition of heat.	4 Thermocouple [T1] placed within the enclosed environment (output) and another [T2] within the HVAC duct upstream of the fan.
Ability to measure power provided to fan and heating element.	Voltage supplied to each device know, Power is collected real-time using LabVIEW.
Ability to measure volume airflow through the system.	User observes differential pressure reading of airflow, from this measurement mass flow rate through system can be calculated using provided equations and background on theory.

Table 3.2 Design description for thermal systems lab

While the control system regulates the HVAC system to achieve a steady-state temperature, the thermal systems lab exercise can be completed. The

lab handout describes the procedures for the collection of data, conversion to SI unit system, and calculation of desired values. The temperature set points of the lab will not exceed 33 ^{0}C for both system configurations. These values were chosen based on time to reach steady-state.

3.2 HVAC installation

This system is used to ventilate an enclosed environment and manipulate the temperature of the air. The system utilizes a fan that pushes air over a heating coil to manipulate the temperature of the enclosed space. The team designed a HVAC system that would meet the specifications and the corresponding design requirements as shown in Table 3.3.

Specification	Design
Provide a constant, measurable flow rate 14.7 CFM	Fan controlled by LabVIEW, verified by taking pressure readings from a differential pressure sensor
Ability to heat air from room temperature to 37.5 ^{0}C	Controlled heating element (obtained from hair dryer designed not to exceed 60 ^{0}C)
System withstands temperature of heating element	Heating element contained inside ABS piping which is rated up to 76.7 ^{0}C which exceeds the element's maximum temperature
System fits inside cart.	System designed to fit inside and on cart 25" x 50" x 32"

System must be able to run both standard and re-circulation flow	Piping, valve, and cap are arranged in such a way that the system can exhaust the air or re-circulate the air.

Table 3.3 HVAC Specifications and Design

The layout of the system was designed to fit within the dimensions of the cart. The scale drawings of the system can be found in plans attached. The system layout found in Figure 3.3 is to scale and also shows HVAC system installed on the cart. When the system is set for a recirculation process, the exhaust valve is closed and the end cap is removed. The exhaust valve is placed such that when it is closed the air is redirected back through the system when the cap is removed. A digital model from ProE of the system denoting the locations of the valve and end cap can be found in Figure 3.5.

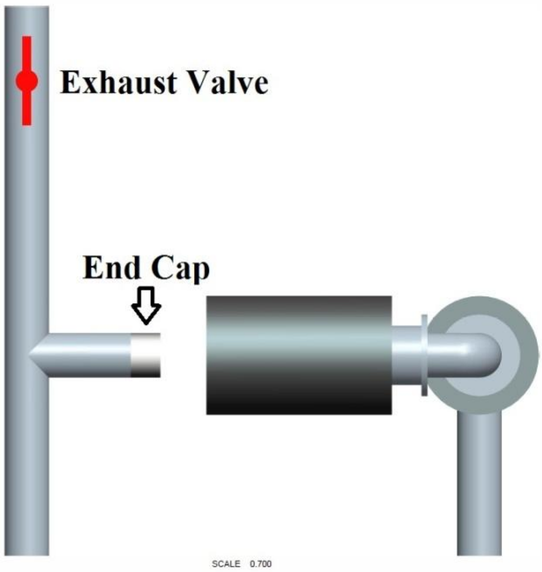


Figure 3.5 Valve and End Cap Locations

The HVAC system's piping, valve, and cap were purchased, assembled, and installed together. The fan and heating coil have also been acquired and installed into the system. The fan and heater are mounted into black ABS housing sections using an adhesive pipe insulation which is rated for temperatures up to 76.7 ^{0}C. ABS was chosen as the housing for the heater because of its high heat tolerance and availability. PVC was used for the remaining sections of the systems piping because of ease to assemble and available sizing. The entire HVAC system has been mounted on the cart and connected to the contained space. The inlet and exhaust pipes extend into the contained space to facilitate the circulation of air through the space.

In order to properly heat and ventilate this system a constant flow rate is needed. The control system varies the heat applied to the flow in order to manipulate the environment. The heating coil used in the system was taken from a hair dryer. Initially the team decided to use a hair dryer's heating element because of its fast response time and small size. While taking the hair dryer apart the team realized the small, inline fan contained with it was an ideal fan for the HVAC system. The fan is almost three inches in diameter and thus fits inside the three inch diameter ABS tubing. By testing the system with the fan and heating coil installed and working the team was then able to determine a proper flow rate. If the flow rate is too low the system will not react quickly enough and heating coil may over heat. If the flow rate is too high the air passing over the heating coil will not get hot enough to adequately heat the enclosed environment. The team was able to find a range of flow rates that worked for the system. (For more information on the flow rate please see testing section, Chapter 4.)

A differential pressure gage has been installed into the enclosed environment. Total and static pressure probes coming from the differential pressure gage are installed into the HVAC system at the same location, shown

in Figure 3.6, after the fan and heating coil housing. The total pressure probe is installed parallel to the airflow using a metal rod to hold it straight. The static pressure probe is installed perpendicular to the direction of airflow. The differential pressure gage provides students with a differential pressure reading in Inches Water Column. Students following the lab instructions will use this value to calculate the flow rate in the system. (The process to calculate flow rate from a pressure reading is shown in the lab instructions.)

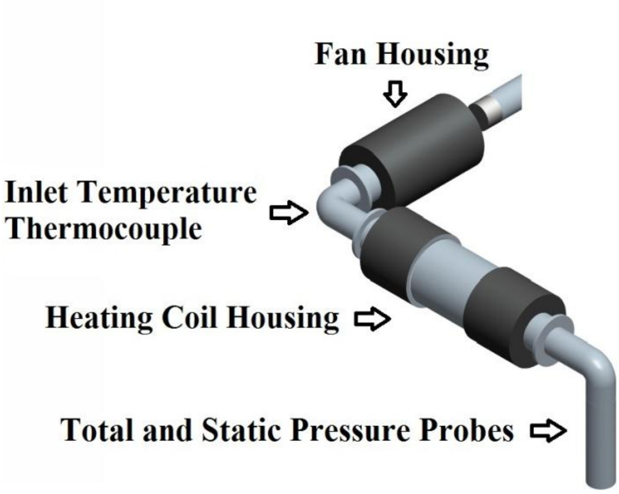


Figure 3.6 HVAC System Layout

Thermocouples have been installed into the system as well. The thermocouples were used to test the ability of the heating coil to heat the air as specified by the user through LabVIEW. Figure 3.6 also shows the location of the inlet temperature thermocouple. This sensor is used to measure the temperature of the air before it passes over the heating coil. Another thermocouple is placed inside of the control volume to measure the temperature of the air after it has passed over the heating coil. These measurements provide feedback to the control system.

3.3 Controls demonstration

The major goal of the controls subsystem is to serve as a practical tool in the design of control systems, which are crucial in the majority of industrial systems.

The main goals that the controls subsystem will allow the user to accomplish are:

- Analyze and observe the main features of the response in a control system: stability, precision, speed, and overshoot.
- Design of controllers through frequency response techniques starting from stability, speed, and overshoot specifications.
- Observe the differences between simulation and real systems.

Some important tasks have to be accomplished in the design of the control system, data acquisition, and components choice. The data acquisition consists of gathering samples of the real world (analogical system) to generate data that can be manipulated by a PC or another electronic system (digital system). The device that transforms the signal used by the computer is the DAQ (data acquisition device).This process can be shown in Figure 3.7.

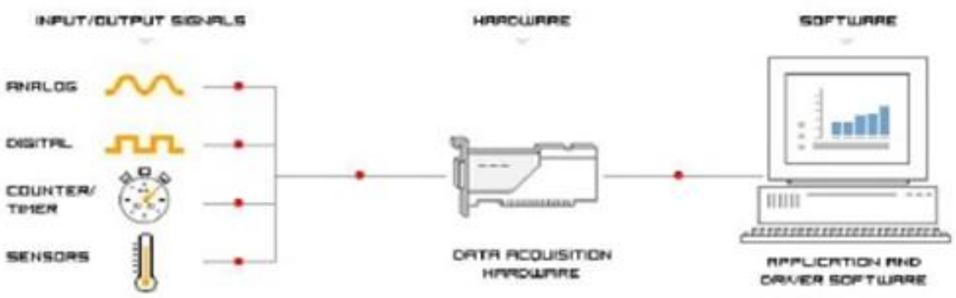


Figure 3.7 DAQ Interface diagram

The three different parts that comprise the subsystem (input/output components choice, DAQ selection/software, and control design) will be explained in-depth:

DAQ selection and software

The DAQ that has been chosen for this project is the DAQ NI USB 6008, which belongs to National Instruments and has the following features [4]:

- 8 analog inputs (+/- 10 volts)
- analog outputs from 0 to 5 volts (12bits)
- 12 digital input/outputs con logic values from 0 to 5 volts.
- Counter of 32 bits

This device is able to carry out multiple tasks simultaneously which means that the USB 6008 can gather information and generate analog and digital outputs at the same time. This capability is indispensable to develop a control system.

Since the DAQ works better with software belonging to the same company (National Instruments), LabVIEW is the most suitable tool to use. LabVIEW is a graphic programming language for the design of data acquisition systems, instrumentation, and controls. In addition, it is compatible with programs or other applications like MATLAB. Thus, the controls design will be implemented in MATLAB, but imported and run in LabVIEW.

Hardware components

The control systems that will be studied is a non-linear SISO system (single input-single output) which means that one variable will be controlled (temperature inside the enclosed environment) through one actuator

(resistive coil). In this sense, the rest of components (fan) will be independently activated from the control loop by the DAQ.

The temperature sensors chosen are 4 NI USB-TC01 thermocouples that will be directly hooked up to the USB port on the computer. These thermocouples will be placed inside the box so they will take an average temperature.

With regards to the output signal of the controller (coil), the DAQ provides very few power (5V and 5mA) so it is necessary to get the power from another source. Since the output of the controller is a variable signal, a PWM block will be implemented and used in conjunction with a relay .The PWM gets a variable voltage level by changing the width of the pulse (D) at the digital output (Figure 3.8).

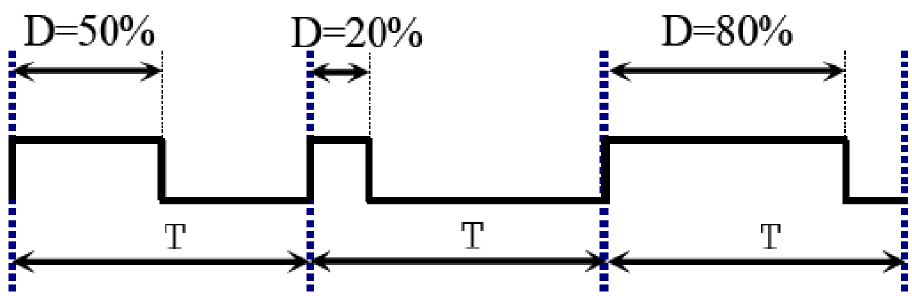


Figure 3.8 PWM

As it was mentioned before the fan will be independently activated using a relay through one of the analog outputs of the DAQ. The relays (from Zetler) used in all the actuators are a general purpose relay that can be used with a 5V microcontroller or control circuitry. The coil draws 72mA when engaged and the relay can switch up to 2A at 30V (or 1A at 125V).

A PCB board has been installed to ensure safety and reduce the number of wires used in the connections. It will contain two slots for the relays and 8 pins for all the inputs/outputs needed as it is shown in Figure 3.9.

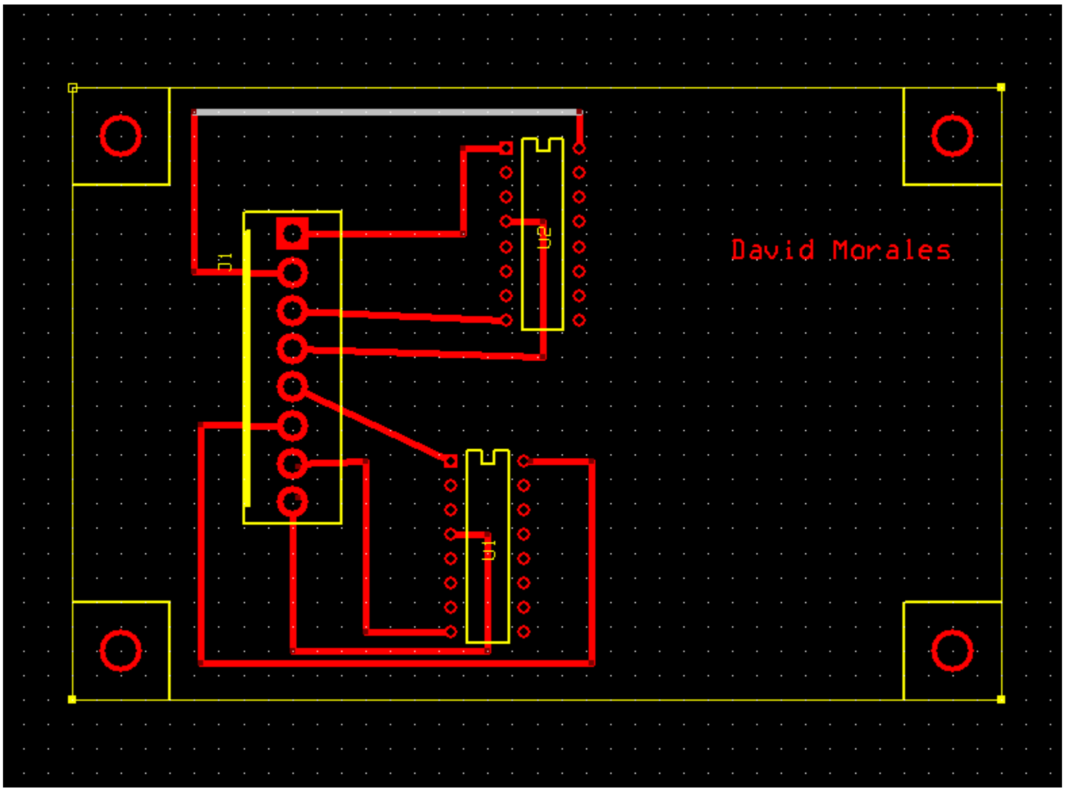


Figure 3.9 PCB board

The two relays will be powered by two transformers (24V each) connected in series and plugged to the wall, so that 48V are obtained. This voltage produces enough heating in the coil and velocity in the fan to reach the requirements.

In short, the analog inputs 0,1,2,3 (AI0,AI1,AI2,AI3) and ground will be used to gather data from the thermocouples; and the analog outputs (AO0/AO1) serve as the control signals for the coil and fan respectively. Figure 3.10 shows all the possible connections in the analog part of the DAQ and the connections that are used are in red [4].

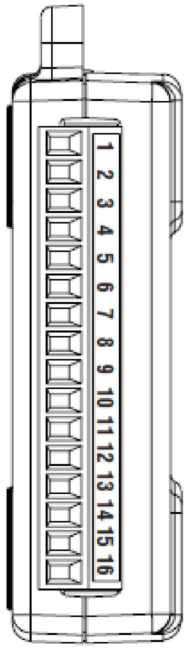
Module	Terminal	Signal, Single-Ended Mode	Signal, Differential Mode
	1	GND	GND
	2	AI 0	AI 0+
	3	AI 4	AI 0–
	4	GND	GND
	5	AI 1	AI 1+
	6	AI 5	AI 1–
	7	GND	GND
	8	AI 2	AI 2+
	9	AI 6	AI 2–
	10	GND	GND
	11	AI 3	AI 3+
	12	AI 7	AI 3–
	13	GND	GND
	14	AO 0	AO 0
	15	AO 1	AO 1
	16	GND	GND

Figure 3.10 DAQ Connections

To make clear all the concepts developed below; Figure 3.11 depicts the flow chart of the entire process.

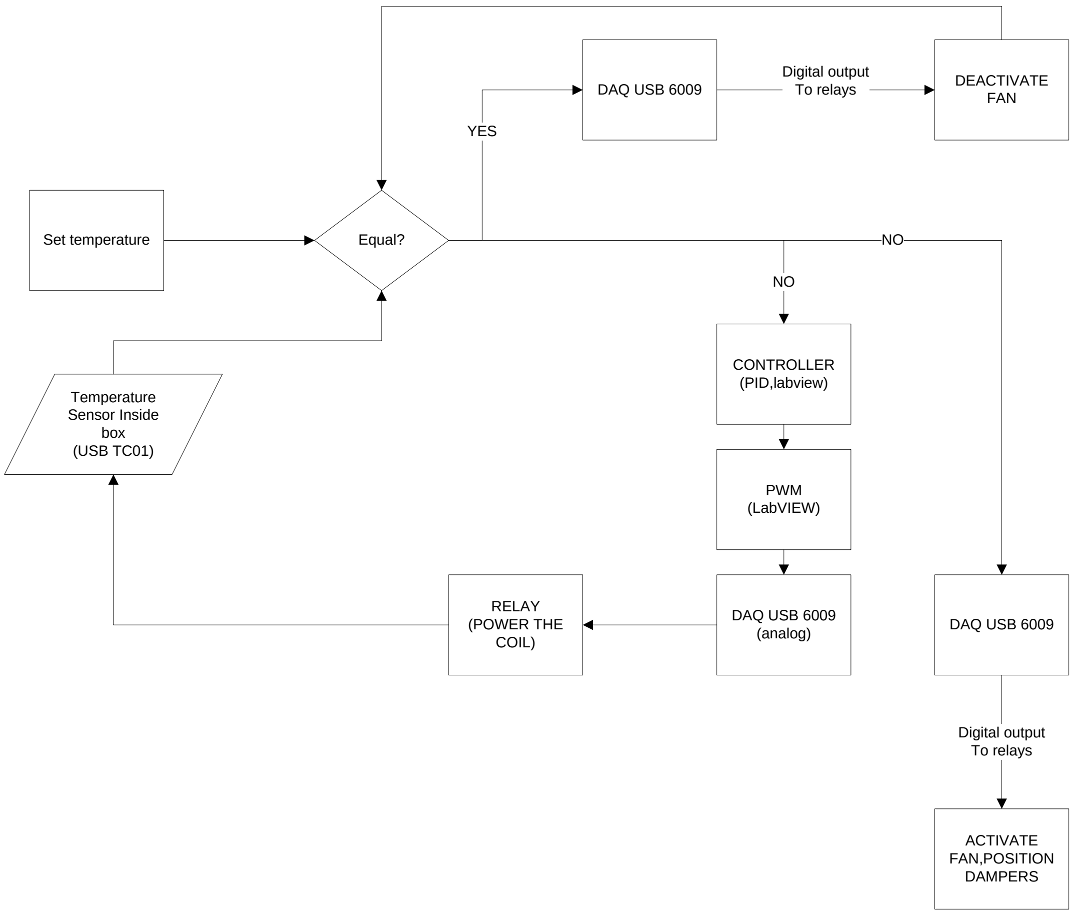


Figure 3.11 Flowchart of Overall Process

Control design

Apart from the possibility to see and manipulate the response of a PID controller, the TOCOM lab aims to allow students to research about the HVAC system, design their own controllers, and test them in the real system.

In order to accomplish this objective the model will be implemented in Simulink (Matlab) starting from the thermodynamics equations for the open loop (no recirculating) shown below. After applying the fist law of thermodynamics [3], Equation 3.1 shows the variation of temperature inside the enclose environment.

$$\frac{dU}{dt} = \frac{dE}{dt} = \dot{Q} - \dot{W} + \dot{m}\ h_{in} - \dot{m}\ h_{out} \qquad \text{(Eq.3.1)}$$

Knowing that:

$$U = mC_vT \qquad \dot{W} = 0$$

It is possible to derive Eq. 3.2:

$$mC_v\frac{dT}{dt} = \dot{Q}_{conv} + \dot{m}\ C_p(Tair - T) \qquad \text{(Eq.3.2)}$$

Where:

- m: total mass of air in the box
- C_v: specific heat at constant volume of air
- $\dot{m}$: constant air flow provided by the fan
- C_p: specific heat at constant pressure of air
- T: current temperature inside the box
- Tair: temperature of the outside air (25 degrees Celsius)
- $\dot{Q}$: Amount of heat provided by the coil through convection.

Assuming no losses, the convection equation [3] gives the total amount of heat transmitted to the air, which depends on the temperature of the coil, area of the coil and the convection factor.

$$\dot{Q}_{conv} = h_{conv} \cdot A_{conv} \cdot (T_{coil} - T_{air}) \qquad \text{(Eq 3.3)}$$

A third equation, which gives the relationship between power applied to the coil, temperature of the coil, and heat transmitted to the air, is needed to complete the dynamics.

$$\frac{\bar{u}^2}{R} - \dot{Q}_{conv} = mC\frac{dT_{coil}}{dt} \qquad \text{(Eq 3.4)}$$

Where:

- $\bar{u}$: Average power after PWM= u (voltage applied) x T(period)

- M: mass of the coil
- C: specific heat constant of the coil

It is important to remember that the use of PWM in the actuator introduces non-linearities, so this model brings the possibility to develop new controllers by finding and setting the operating point and getting a linear model. Once the linear model is obtained it is possible to study the frequency response starting from the transfer function and design another controller which will make the system obtain the different specifications.

The set point that has been chosen is 28 °C for the temperature inside the box.

Using Eq 3.2, 3.3, and 3.4, final non-linear system's schematic implemented in Simulink is shown below in Figure 3.12.

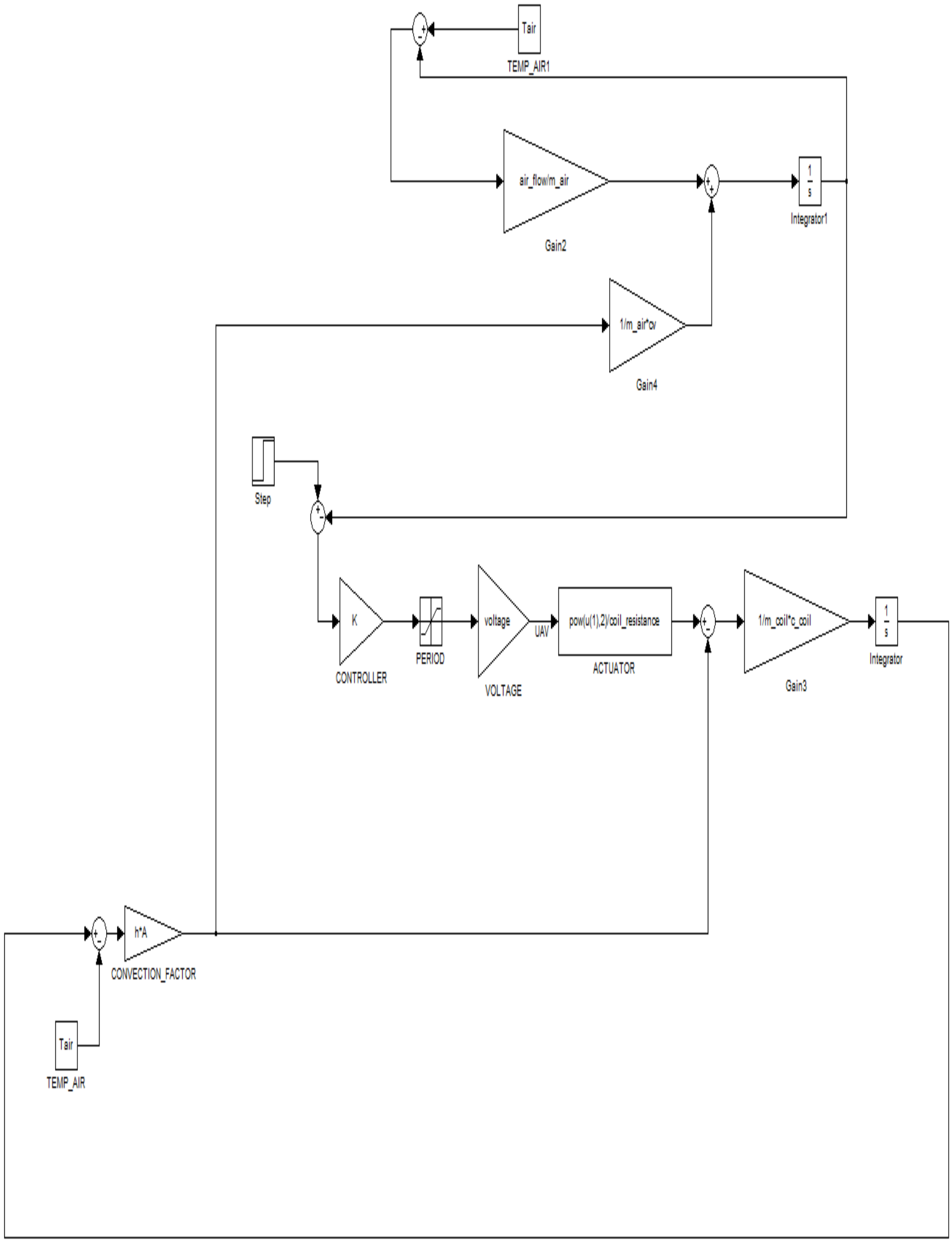


Figure 3.12: Simuling schematic model

Dynamic's initial parameters are calculated to run the simulation:

- Voltage=60
- Tair= 25°C
- M_Air (mass of air in the box)= 0.15 Kg
- Air flow ($\dot{m}$): Using the set point in Table 4.3, 14.75 CFM= 0.008 Kg/s.
- Cv=1012 $\frac{J}{Kg{\cdot}°K}$

Knowing that the coil utilized is made of Nicrom (density= 8400$\frac{Kg}{m^3}$), the following values are obtained:

- M_coil (mass of the coil): 30 gr.
- C_coil(specific heat constant of the coil made of Nicrom): 450 $\frac{J}{Kg{\cdot}°K}$
- A (Area of coil) = 62.83 cm^2
- Coil_resistance=10.25 Ω

Assuming turbulence air flow and forced convection, the convection factor obtained is:

- h=47W/m^2°C

Thus,the non linear system model brings the possibility to come up with a linear transfer function around the operating point.The procedure consists on taking the output and input of the plant (Figure 3.12) in the operating point and apply and iterative algorithm to get the value of the transfer function parameters when the error approaches to zero. Since the plant includes an integrator it is necessary to add a close-loop proportional controller to the plant, so that the identification can be obtained without unestabilities. In this case a proportional controller of K=0.2 has been applied successfully. Files programmed in Matlab for identification are included in the Appendix, Chapter 3.

Finally, the linearization allows to design the final controller to be implemented in the system.

Considerations in controller design

The implementation of both analog PID controller and PWM give rise to a discrete controller which means that the period of the PWM is crucial when it comes to design the controller. An unsuitable choice of the period can lead to an unstable response.

To make clear the limitations of the design Table 3.4 shows the ratio between the speed in open loop (controller design multiplied by the plant) and the period of sampling (PWM)[1].

After designing the controller this ratio has to be checked so that it has to be in the range of small. If the controller is not included or close to the range it has to be redesigned or the PWM period changed.

Period	Big	Medium	Small
wTs	2	0.5	0.1

Table 3.4: Discrete periods

In this case, the period utilized should not be a problem since the constant time of the process (temperature dynamics) is big enough to use a big range of periods. A range from 1sec. to 10 sec is recommended.

Finally, a PID controller will be provided with the aim to be a reference for future comparisons between controllers [2]. PWM parameters are also included:

- Kp=10
- Ki=0.1
- Kd=0.01
- Precision=25
- PWM period=5 sec.

- Amplitude=5

LabVIEW interface.

As mentioned before, the LabVIEW interface should include the controller in charge of activating the actuator of the controlled system (coil) and the fan.The standard controller implemented is a PID, which will be used in conjunction with Pulse Width Modulation (PWM) to activate the relay of the coil, so the analog output signal of the controller is converted into a digital signal [5]. Users will be able to configurate PID and PWM parameters.

LabVIEW interface is shown in Figure 3.13. LabVIEW schematic including controller and PWM is shown in Figure 3.14.

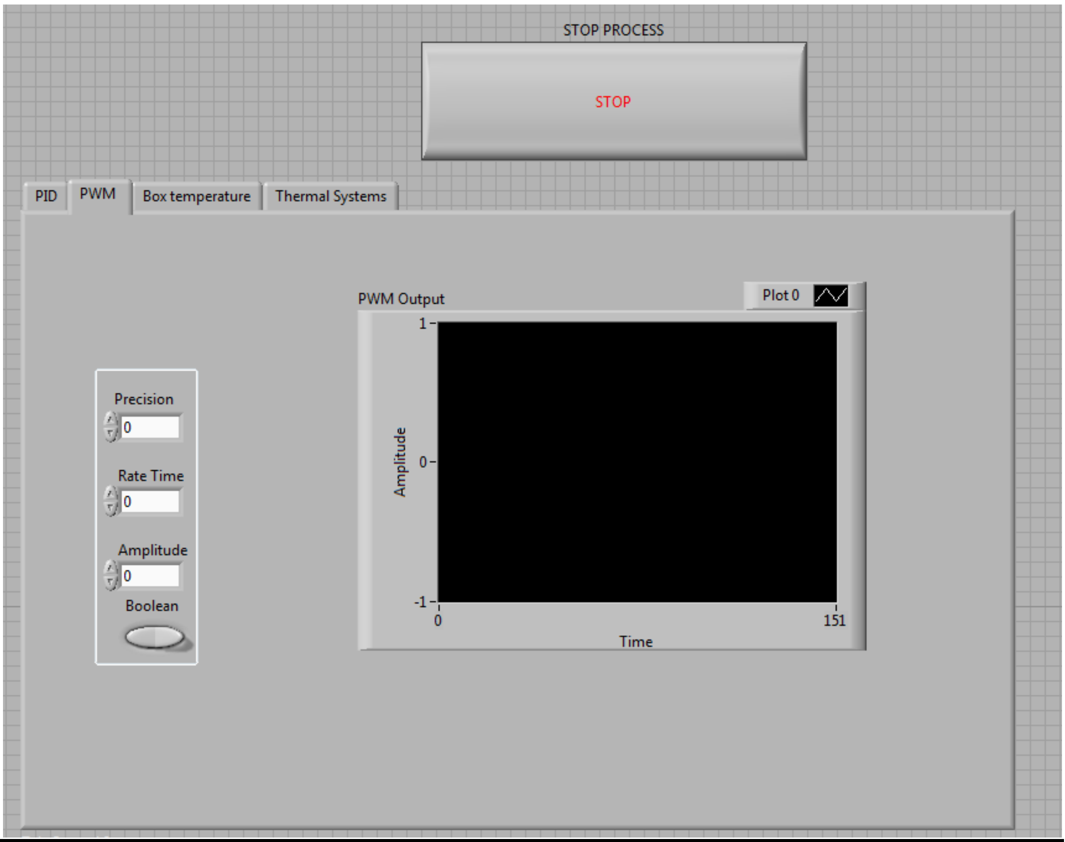


Figure 3.13: PWM LabVIEW interface

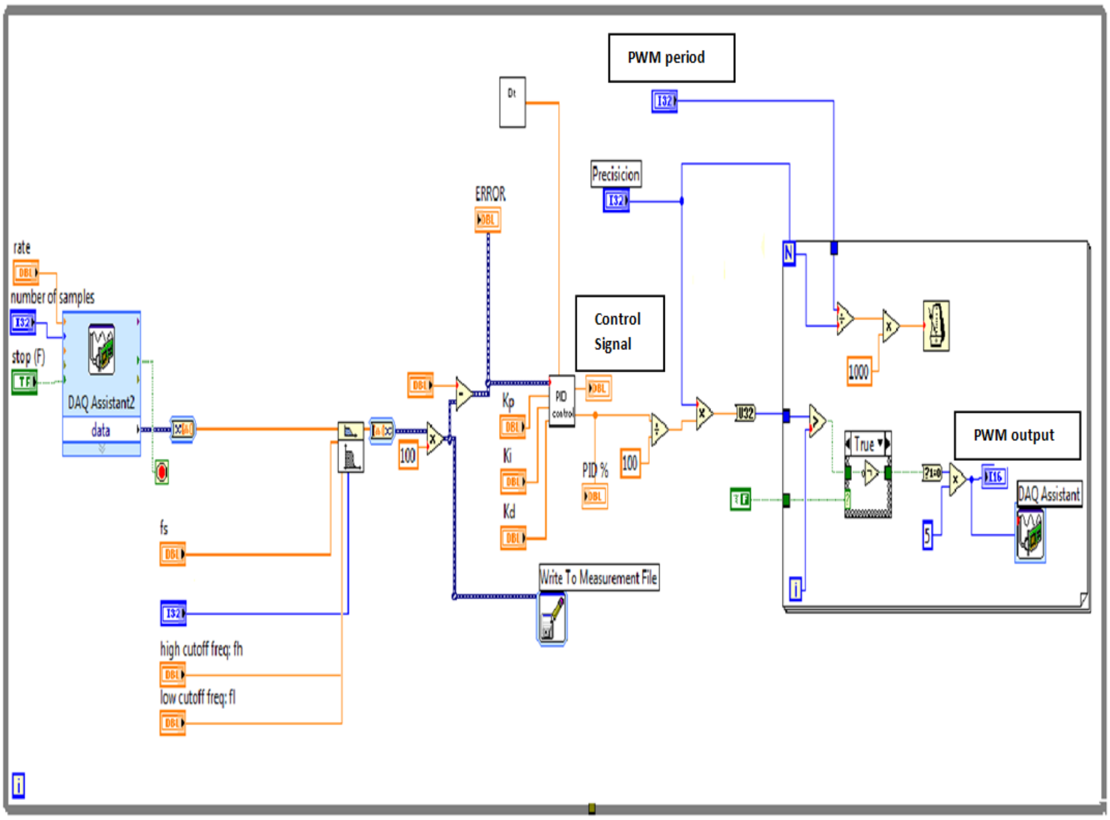


Figure 3.14: LabVIEW programming.

In short, Table 3.5 and Table 3.6 show the specifications and the corresponding design that the controls subsystems must meet.

Specifications	Design
Accurate integration of components in the control system	4 USB thermocouples as inputs and 2 digital outputs (coil and fan).
Provide enough power to the actuators (fan, coil, dampers)	Use of relays
Accurate control response	Provide a PID controller as a reference to comparece it

	with other controllers.
Intuitive interface using LabView	Interface that allows to introduce the controller parameters, PWM parameters, and the desired temperature easily.

Table 3.5: LabVIEW specifications

Specifications	Design
Provide a tool that identifies the transfer function of the system.	File that calculates the parameters of the transfers function's plant by using an iterative algorithm.
Provide a tool that gives the parameters and expression of a certain PID controller for specific requirements.	File that provides the parameters of the PID controller given the different specifications.
Bring the possibility to export the results from Matlab to Labview and see the differences between simulation and real system.	Intruduce a file that exports data to an excell file.

Table 3.6: Controls lab specifications

3.4 Controller and sensors

The controller and sensor subsystem includes the installation, wiring, and programming of the controller and sensors involved in the Siemens Display. Table 3.7 shows the design specifications for the subsystem.

TOCOM Lab Siemens Display	
Specifications	Design
Fire pull switch that triggers alarm	Controller detects when digital input is triggered by pull switch. Controller enables light and alarm.
Actuate the sample damper	Controller rotates the damper on command to simulate airflow.
Wall switch that indicates occupancy	When user triggers the switch, system responds to occupancy and enables fan
Implement temperature, humidity, and CO2 sensors on a mobile unit	All components were placed on a 26.5" x 24" backboard on the cart

Table 3.7 Design specifications.

The controller being used is the PXC Modular Series (PXC100-PE) shown in Figure 3.15. This controller has the capability to be expanded using Terminal Blocks, or input/output (I/O) modules, with support for up to 500 I/O points. These points are for connecting sensors, actuators, switches and buttons. The Terminal Blocks can be selected and added on to the controller based on the type of job needing to be accomplished. Each block has different capabilities [6],[7].

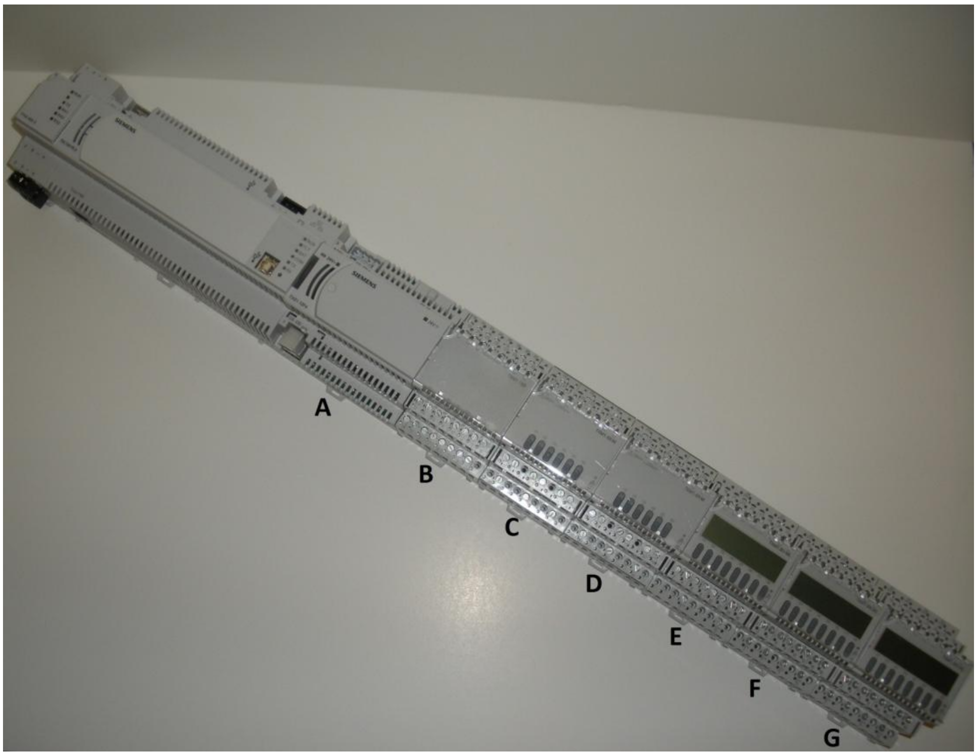


Figure 3.15 PXC Module with Terminal Expansion Blocks.

The first block, shown in Figure 3.15 (block A), is the power supply (TXS1.12F4) for the I/O Modules. It has a 24 VAC (volts of alternating current) input used to power it and the expansion blocks. The power supply also converts the 24 VAC into 24 volts direct current (VDC) to provide power for some of the sensors and other components that require DC.

The next module, in Figure 3.15 block B, is a 16 point digital input (DI) block (TXM1.16D). Refer to Appendix (Table 1.1, Chapter 1) for input and output descriptions. This module monitors normally open or normally closed dry contacts (voltage free) for up to 16 inputs. The third block, in the same Figure 3.15 block C, is a digital output (DO) module with manual override (TXM1.6R-M). This block provides six normally open or normally closed voltage free contacts with a maximum rated voltage of up to 250 VAC at 4 amperes (A). The override button allows for each point to be controlled manually on the Terminal Block itself. It has green light emitting diodes

(LEDs) for each point on the module. The fourth module is the same as the third.

The last three modules are universal blocks (TXM1.8U-ML/TXM1.8X-ML), shown in Figure 3.15 blocks E, F, G. Each of the eight points of the individual blocks can be configured as a DI, analog input (AI), or analog output (AO) to meet specific application needs. This block also features a liquid crystal display (LCD) that displays information for each I/O point on the module: configured signal type (input or output), symbolic display of process value (a bar indicating how much voltage or current is being measured), and notification of faulty operation, short circuit, or sensor open circuit. The blocks also have outputs for 24 VAC and 24 VDC to power the sensors and components.

The controller and all the expansion Terminal Blocks provide more than enough points for all the sensors and components that will be connected. There will be two different types of temperature sensors, a CO_2 sensor and a humidity/temperature sensor.

The two types of temperature sensors that Siemens produces are the room and duct sensor. The room sensor (540-680FB), shown in Figure 3.15, is a wall mountable unit with an LCD on the front of the unit to display current temperature in degrees Fahrenheit (F) or Celsius (C). The unit can measure the temperature range from 55° F to 95° F (13°C and 35°C) and has a set point slider under a small cover in the front with the same range. It uses a 10K Ohm thermistor with ±0.5% accuracy, similar to that of the duct sensor (shown in Figure 3.16). The duct sensor is a rod with a base attached to the end of the unit. The tip of the rod is placed inside a duct to measure the temperature. Duct sensors are common in areas where a wall mounted sensor may be tampered with or damaged. They can be placed out of sight, in the return duct of a room.

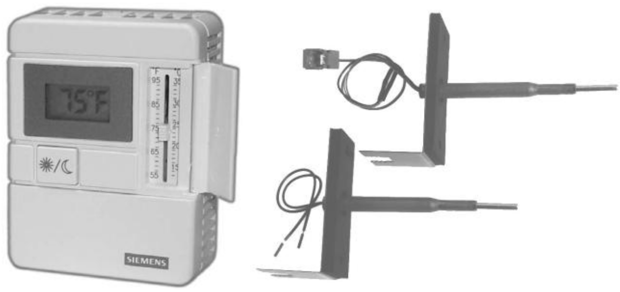


Figure 3.16: Siemens Room Temperature Sensor (Left) and Duct Temperature Sensor (Right)

An air quality sensor (QPA2000), refer to Figure 3.17, is important for determining the level of CO2 in a room. It determines the amount of CO2 in parts per million (ppm) and creates a 0 to 10 VDC linear proportional output signal. The sensor has a range of 0 to 2000 ppm. Outside CO2 levels generally vary between 300 and 400 ppm while room levels should not vary higher than 600 to 700 ppm. If the level reaches 600 ppm in a room, then the ventilation system needs to cycle fresh air throughout the enclosed environment.

Figure 3.17: Air Quality Sensor (CO2)

Relative humidity can be measured using the sensor in Figure 3.18 (QFA3171D). This high accuracy device can measure temperature from 0°C to 50°C (32°F to 122°F) and relative humidity from 0 to 100%. The device outputs

a signal of between 4 to 20 mA for the temperature and relative humidity levels.

Figure 3.18: Relative Humidity/Temperature Sensor

To actuate the damper in the model Variable Air Volume (VAV) box, shown in Figure 3.19, an Actuating Terminal Equipment Controller (ATEC) is used (550-405). This unit contains an actuator that controls a damper as well as has two AIs and two DOs for other components. The controller also features a high/low pressure differential sensor and a connection for a room or duct temperature sensor.

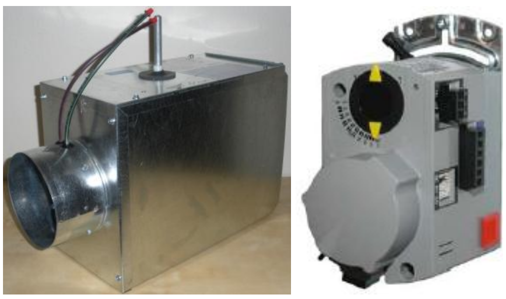


Figure 3.19: Variable Air Volume Box (Left) and Actuating Terminal Equipment Controller (Right).

Wiring the components depends on the different types of signals being outputted to the controller. All the temperature sensors work by varying resistance, which requires an AI on the controller. However the override button on the room temperature sensor unit sends either a high or a low

signal, therefore requiring a DI on the controller. The relays are connected to the dry contact DOs with 24 VAC feeding them from the transformer. When the DOs are triggered, the connection is closed and electricity from the transformer activates the coils on the relays.

The humidity and CO2 sensor vary current and voltage, respectively, so they both require AIs on the controller. The fire pull station consists of a button that is constantly depressed until triggered by a user. When the user pulls the fire alarm, the button is no longer depressed, therefore creating a closed connection to a DI on the controller.

There are several programs, written in Insight, that are required to run some of the components on the Siemens display board. These programs tell the controller what to do with the I/Os. For instance, the Fire Pull Switch Program tells the controller to enable an output when it receives an input. In other words when a user pulls the fire alarm, the controller detects the input from the button on the fire station and enables the output to the siren, as well as turns off the VAV box fan to prevent the circulation of smoke.

The next program is the Occupancy Switch Program. This program simulates a person walking into the room. When the switch is flipped on, the system knows someone is present and turns on the HVAC system, the fan in the VAV box and slightly rotates the damper in the VAV box. The programs can be viewed the Appendix (Figure 1.1 and 1.2, Chapter 1).

3.5 Guide User Interface (GUI)

The GUI subsystem is designed to allow any user to interface with the entire system and learn about control system with ease. What separates the design of TOCOM lab from other controls laboratories is the ability to interact with the system via the GUI. As a result the GUI must meet the following

specifications and the chosen GUI design to meet those specifications is listed below in Table 3.8.

Specifications	Design
Display Temperature, CO2, and Humidity	GUI has values displayed
Display Alerts and Alarms	Alerts and Alarms appear in GUI when triggered
Easily navigatable GUI	All font must be at least 14pt All descriptions of objects must have pictures included All background colors must be easy to see colors (Blue, Red, Green, Black, White) A home button and a back arrow included on every page with exception of first page Follow Ergonomic (Human Factor) standards for all graphs
Switch to activate VAV system	Added a switch that turns entire VAV system to on position through Insight

Table 3.8: Specifications and Deliverables for GUI

The first major design decision was what program to run the GUI on to satisfy all requirements. There are many options that were explored and, in some cases, created to evaluate which program should be used (Simulink, MATLAB). However for all the sensors to be integrated with the GUI the program that should be used is Insight, a Siemens created program. Insight displays all sensor values on a series of graphs along with the ability to manage the overall system.

While Insight was chosen to create the GUI, it also had drawbacks that needed to be modified for the program to accomplish all goals outlined.

Insight's major drawback was that it was designed for Siemens employees and not meant to be user friendly. The program is built to store information and allow anyone with knowledge of Siemens programming to access the system. This was not acceptable as the GUI needed to be easy to use for anyone not just those with an intimate knowledge of Insight. The solution was found in Micrografx Designer, a program that interfaces with Insight that allows for pictures, diagrams, schematics, and other more user friendly data to be uploaded.

Now with the chosen programs in place the first step in the design was to create a format that allows the system to be easily navigable and also outline areas where sensor readings could be displayed along with all other relevant information. To make sure the GUI could be used with ease the following rules were applied to the design.

Now that these criteria had been established, the GUI homepage was created as seen in Appendix (Figure 1.3, Chapter 1).

The rest of the pages were built with the next page called "First" that shows all the different sensors and gives links that navigates to each sensor's reading (Refer to Appendix). Each sensor page has the current value displayed and if the user wishes for a larger window they can click on the image.

Also on "First" is a link to the "Design" page which is created for a more in-depth understanding of the system. The "Design" page outlines each individual component including a picture, description, price, and how it was incorporated in the lab. The purpose of these pages is to show an engineer how the system was built and how they could replicate the design in a system that they would build. The design pages can be found in Figures 1.4-1.11 of Appendix, Chapter 1.

Once all pages were created a new problem surfaced, navigating through the pages. Any person who has experience with Insight found this process easy, but when a sample of students were shown the GUI as it was at that time, not one could see an easy way to go back through the pages. Given this information, it was decided that two buttons should be placed at the top right and left of each screen that gives the user the option to go back to the last page (shown by a green arrow in the top left corner) and return back to the homepage (shown by a House in the top right corner). The images for each navigational button are shown below in Figure 3.20.

Figure 3.20 Back and Home buttons

To meet the design goal of displaying the values, we first created point addresses. These point addresses assign each sensor a point that is called in the GUI to display the reading from that sensor. When a user clicks on a sensor, the readings from that sensor are sent to the point created and subsequently displayed on the page. The points created are seen in Figure 3.21.

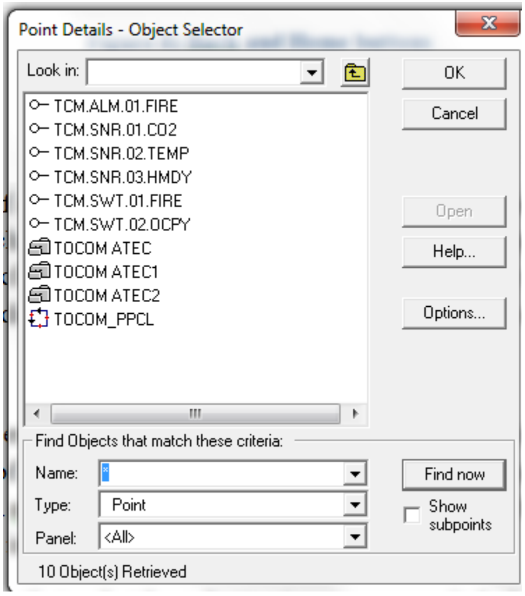


Figure 3.21: Created Points Menu

With the pages built and sensors integrated, we created alarms for each sensor to message the user if the values are out of acceptable ranges. For example if the reading for the CO2 sensor exceeds 600 parts/million an alarm appears on screen informing the user that the value is too high. An example of what the user observes can be found in Figure 1.12 Appendix, Chapter 1.

The next specification says that a shutdown button/ occupancy switch should be able to turn the system on and off. This means that a switch is placed on the board that when turned to the on position the VAV begins to push air through the system and when turned to the off position no air flows through the system. To meet this goal, a switch is placed in the system that when turned on causes the VAV to turn on. When turned on, the VAV box begins to turn the damper and the fan switches on. The temperature sensor in the VAV also changes values which are displayed on the screen.

Chapter 4

Implementation

4.1 Construction

The TOCOM Mobile Cart has been constructed to the design specifications described earlier. The CAD rendering of the unit, with primary components of all systems is shown in Figure 4.1. The completed construction is shown in Figure 4.2 and 4.3.

Figure 4.1: CAD Rendering of the TOCOM Mobile Lab

Figure 4.2 Photograph of TOCOM Mobile Lab, air control system and HVAC system

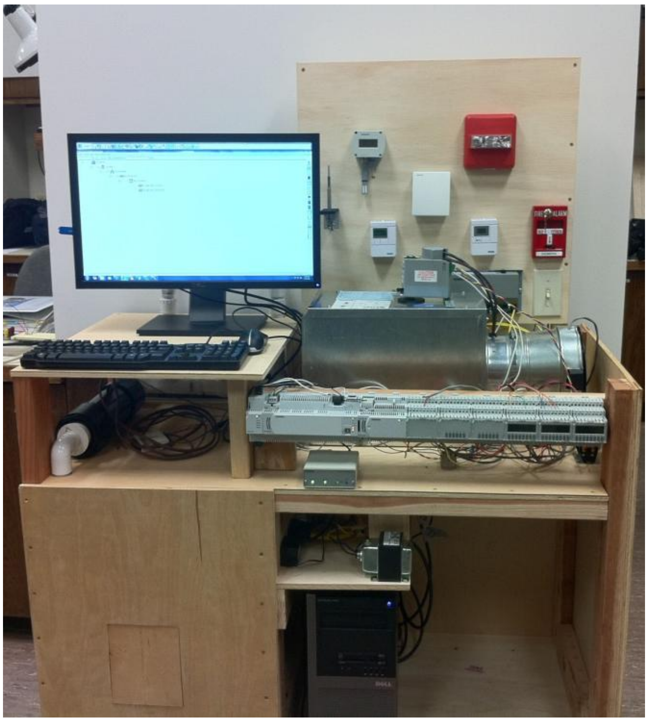


Figure 4.3: Photograph of the TOCOM Mobile Lab featuring Siemens Component Display

HVAC System Construction

The main body of the HVAC system through which the air travels is made of PVC tubing. All tubing was purchased in two feet lengths and then cut to size using a horizontal band saw. Pipe cement was used to connect some portions of the system while others were pressed together to allow for disassembly and maintenance. Figure 4.4 shows a computer model of the entire system. This figure was chosen over a picture of the physical system because the system cannot stand free on its own.

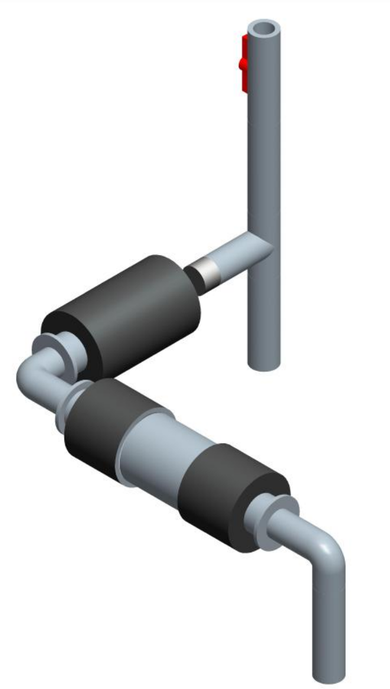


Figure 4.4: HVAC System construction: ducts

The heating coil enclosure made of abs tubing is shown in Figure 4.5; the system is mounted onto the wooden cart. The brown wires running into the tubing are used to power the heating coil housed inside.

Figure 4.5: Heating Coil Enclosure

Fan and heating coil used were mounted into the system using an adhesive insulation tape. The heating coil came incased in a heat shield (not shown). The adhesive tape was wrapped around the circumference of each device and then installed into the ABS tubing. The PVC tubing was used as the main body of the system. The valve and cap were also made of PVC. The valve, cap, and ABS fan housing are shown in Figure 4.6. The system in this figure is in the standard flow configuration meaning the system would be taking in outside air, circulating it through the system, and then dumping back into the outside environment if it were running. In this configuration the exhaust valve is open while the end cap is attached. The end cap prevents hot air from running back through the system.

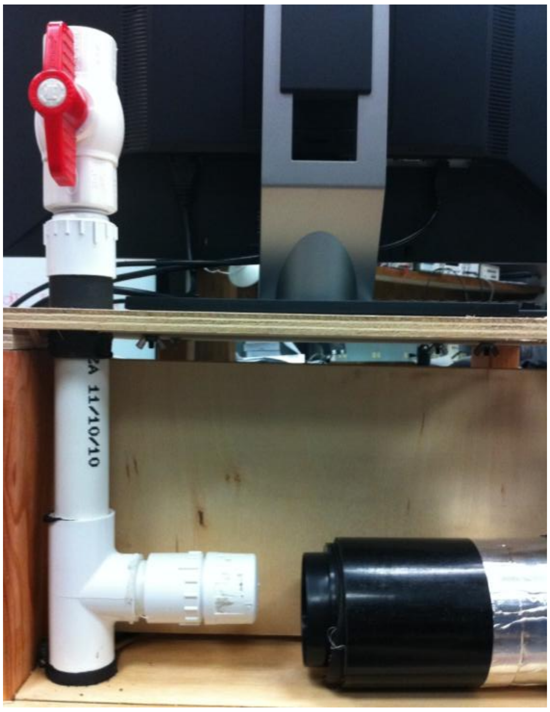


Figure 4.6: System in Standard Flow Configuration

In a reheat configuration the system re-circulates air from the box some of the air from the box. In this configuration, the exhaust valve is closed while

the end cap is removed thus allowing the air to be re-circulated and reheated. The reheat configuration is shown in Figure 4.7.

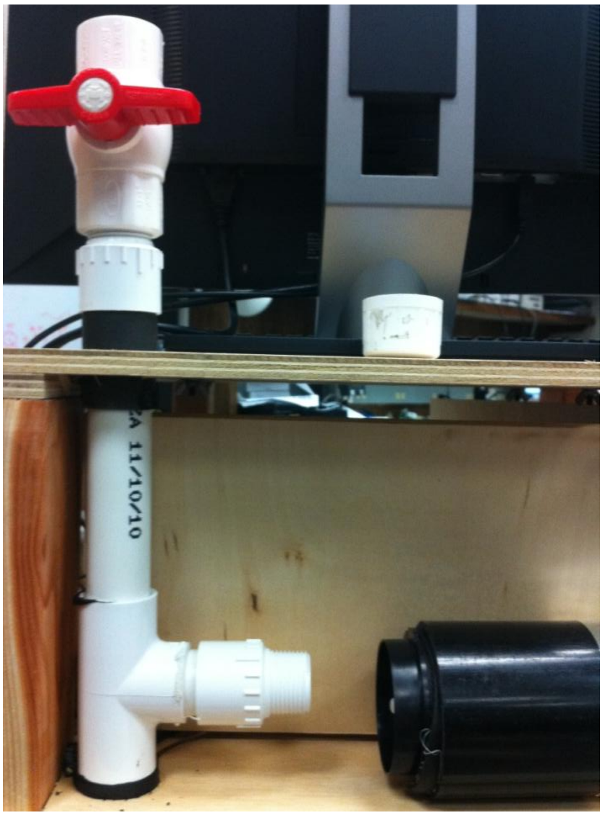


Figure 4.7: System in Reheat Configuration

The differential pressure gage is shown in Figure 4.8 through the clear wall of the cart. The gage is mounted inside the enclosed environment and measures the differential pressure in the system. (Note: Further information on the differential pressure gage can be found in both the Design and Analysis section and the Testing section)

Figure 4.8: Differential Pressure Gage

Lengths of clear tubing, which are used as the probes for the differential pressure gage, installed in the system and attached to the back of the differential pressure gage, are shown in Figure 4.9. The metal pipe seen running into the PVC tubing is used to hold the total pressure probe parallel with the flow of air.

Figure 4.9: Probes Connected to System and Differential Pressure Gage

4.2 Testing

4.2.1 TOCOM Mobile cart

The TOCOM Mobile Cart was tested in a few specific areas concerning mobility and support of onboard subsystems. The testing method and results are outlined in Table 4.1.

Customer Requirements	Testing	Evaluation of Results
Enclosed environment enabling temperature control	Temperature increase without gross loss of heat input	Pass
Portable lab unit to be used throughout Loma Hall	Maintained assembly and mobility while moving through Loma Hall	Pass
Stores and provides space for onboard computer used for control of subsystems	All computer components can function and be interfaced with	Pass
Provides space for onboard HVAC and air-recycling loop	Observe that HVAC system functions in the provided space	Pass
Provides space for demonstration of Siemens components	Siemens components fit within the allotted space, allowing easy access for demonstration	Pass

Table 4.1: Testing Methods and Results for Mobile Cart

The primary focus of the testing for the TOCOM Mobile Cart was on mobility. The cart was moved through engineering laboratories and onto the elevator in the building; the successful transportation of the lab shows that the requirement is met.

The design of the system accounted for the space needed by the supported subsystems; this requirement was met upon the completion of construction. All components for the other subsystems fit on the cart and were positioned to facilitate user interaction.

The integrity of the enclosed environment has been confirmed by the successful addition of heat into the air within the system without excessive heat loss, enabling the control system to achieve a steady-state temperature. Heat loss within the system was unavoidable and necessary to achieve steady state at an elevated temperature. Achieving the steady-state condition at an elevated temperature demonstrates the functionality necessary for the thermal systems and control systems lab exercises. An excessive loss of heat would have prevented the system from reaching an elevated temperature, indicating leakage of the air in the enclosure. Efficiency of the system was revealed in the testing of the thermal systems lab.

4.2.2 HVAC

Throughout the project the team has continuously tested and adjusted the design and parameters of the HVAC System. The system configuration has been redesigned a total of four times. The first system contained automated valves but through testing it was determined that the system could not achieve the necessary pressure for the valves to function properly. The second system was a similar layout to the first but contained all hand actuated T-valves, requiring manual system adjustment. As testing was conducted on this system the team found that the fan being used could not withstand the high temperature of the exhaust at the inlet and as a result the team burned out a fan. The team then designed a system utilizing a Daton AC Axial Fan which could tolerate a high inlet temperature. Although the fan was rated for 115 cubic feet per minute (CFM) flow team found through testing

that the fan did not provide a measureable pressure differential as required by the labs. The finalized HVAC design uses a hair dryer fan at an open inlet and utilizes an open air mixing process for the exhaust allowing for a lower inlet air temperature during a reheat cycle.

To test the finalized HVAC system design the team took the customer requirements and developed testing procedures for each one to evaluate the team's level of success. Table 4.2 below outlines the requirements, testing procedures, and resulting outcome from each test.

Customer Requirements	Testing Procedure	Evaluation
Ability to provide a constant, measurable flow rate.	Conduct a series of tests in which the system is run using different temperature specifications set in LabVIEW. During tests observe the differential pressure gage to determine if there is a significant change in pressure, indicating a change in flow rate.	Pass
Ability to heat air from room temperature to 33 degrees Celsius	Run the system at its maximum allowed temperature set (33 degrees Celsius). Using the reading from the thermocouple determine if the system reaches the set temperature.	Pass
System withstands temperature of heating element	Heating element contained inside ABS piping which is rated up to 76.7 degrees Celsius which exceeds the elements maximum temperature. Run the system at its maximum allowed temperature set (33 degrees Celsius). Observe system to see if any deformations form. (Note PVC piping is rated to 60 degrees Celsius)	Pass
System fits inside cart	System designed to fit inside and on cart 25” x 50” x 32”. System was built and then installed onto the cart.	Pass
System must be function as both standard and reheat flow	Test valves first by turning red handles to ensure they rotate a full 90 degrees. Then conduct Thermal Systems Lab written for this lab equipment	Pass

Table 4.2: HVAC Testing

To test the ability of the HVAC system to provide a constant flow rate the team ran a series of tests using ten different user specified temperatures in LabVIEW. Each test took a different amount of time because the system had to reach a different temperature each time. Once a test began a team member watched the differential pressure gage. If the reading on the gage had changed it would have indicated a change in flow rate. In each of the tests the readings from the differential pressure gage remained constant and thus the flow rate remained constant. During these tests the team was also adjusting the amount of power provided to the fan. The team found that at very high speeds the controlled environment would not heat up because too much air was running over the heating coil rendering it ineffective. When the fan was running too slowly the heating coil would begin to get too hot. During one of the tests the team burnt out a heating coil because there was not enough air flowing through the system. The team determined that the fan powered at 24 volts provides a flow rate of 14.7 CFM through the system. This flow rate allows for the system to react quickly while not flooding the heating coil with too much air.

The operator verified before testing the system that the valve and cap worked properly. When testing for the maximum temperature the system could achieve, the team found that that the system in the reheat configuration achieved a higher maximum temperature than the system could in the standard flow configuration. The maximum temperature the system can achieve for the reheat configuration was found to be 37.5 degrees Celsius. The maximum temperature the system can achieve for standard flow was found to be 35.75 degrees Celsius. The team decided that for the lab there should be a cap on how high students can set the temperature that does not reach the maximum the system can achieve; thus in the lab the highest temperature set is 33 degrees Celsius. The team decided to do this because it

takes close to twenty minutes for the system to reach its max temperature; where as it takes less than ten minutes to reach a steady state at 33 degrees Celsius.

	Differential Pressure	**Flow Rate**
	Inches W.C.	CFM
	0.4	9.839609
	0.5	11.00102
	0.6	12.05101
	0.7	13.01658
	0.8	13.91531
Operating Point	**0.9**	**14.75941**
	1	15.55779
	1.1	16.31715
	1.2	17.0427
	1.3	17.73861
	1.4	18.40822
	1.5	19.05432

Table 4.3: Differential Pressures and Corresponding Flow Rates.

Throughout all of the tests, including the maximum temperature tests, the housing for the fan and heat coil as well as the piping stayed intact and without any type of structural failure.

4.2.3 Controls

The running of the real system has been accomplished: effective gathering of information transmitted by the sensors, transmission of control signals, actuators powered by relay/transformers, and implementation of the final controller in LabVIEW. Table 4.4 shows all the specifications with their corresponding testing procedure.

Specifications	Testing	Evaluation
Accurate integration of components in the control system	Correct interfacing between components: temperature acquisition (thermocouples) and transmission of control signals through the DAQ. See if the values gathered in LabView match with the real values.	Pass
Provide enough power to the actuators (fan, coil)	Implementation of two transformers that provide 48 and 24 volts to power coil and fan. Test of the appropriate running of the components (pipes, coil, fan).	Pass
Accurate control response	Test the reference PID controller and see if it achieves the requirements and effectively controls the temperature.	Pass
Intuitive interface using LabView	Distribute a survey to students and and receive feedback.	9/10

Table 4.4: LabVIEW Design Specifications and Testing.

4.2.4 Control systems lab

The controls lab has been tested separately from the overall controls systems and the results are seen below in Table 4.5.

Specifications	Testing	Evaluation
Provide a tool that identifies the transfer function of the system.	Compare the outcomes of the linear and non linear system and see if they are reasonable (less than 10% error between them).	Pass
Provide a tool that gives the parameters and expression of a certain PID controller for specific requirements.	Test the file for the following requirements: • Overshoot of 20% • Stability margins of at least 30° (distance of $w_u$and w_0 from x, y axis.) • Quickest settling and rise time for these limitations.	Pass
Bring the possibility to export the results in Matlab to Labview and see the differences between simulation and real system.	Test the real system and simulation for different values of the PID controller.	Pass
Friendly guide to do the lab	Attempt of the team members to do the lab in their own.	Pass

Table 4.5: MATLAB Specifications and Testing.

The plant of the system is an integrator affected by a non-linear effect of the actuator. This means that the response tends to be infinity in open loop, so it is necessary to close the loop and proceed with an identification of the plant. The file that originally was developed for the linearization was based on the commands ‘trim’ and ‘linmod’ in Matlab, but unfortunately they can only be applied to stable systems in open loop. To correct this problem a new file was created, so it has been possible to do the identification. It is based on the application of an iterative algorithm that solves the parameters of the transfer function for a given input/output obtained from the non linear system simulation.

Testing successfully reached the expectations. The PID controller, that the file in Matlab gives, has been tested and checked manually for the same specifications indicated above in Table 4.5.

The sample lab guide that students will be performing can be found in Appendix, Chapter 3.

Finally, both simulation and real system responses have been gathered and compared to ensure that the identification is accurate. Both responses were exported to an excel file as shown in Figure 4.10.

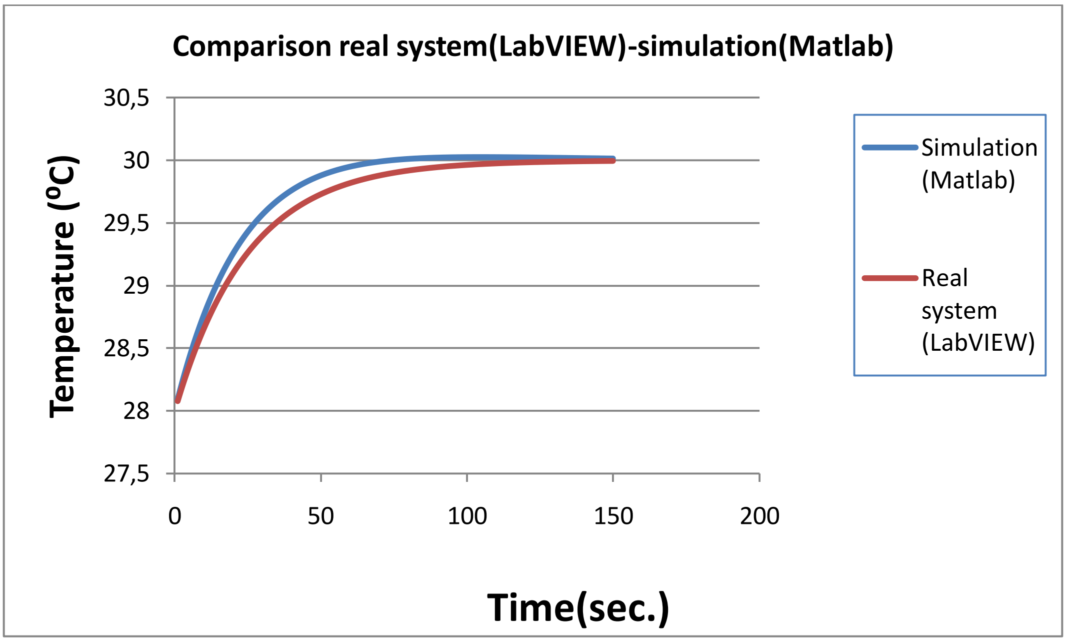


Figure 4.10 Comparison real system (LabVIEw)-simulation (Matlab)

As it can be inferred from Figure 4.10, the approach to the real system made by the system identified is accurate. The PID reference-cotroller mentioned in chapter 3 was implemented to obtain these responses (Kp=10, Ki=0.1, Kd=0.01). Both responses show a similar shape and reach the steady state at the same time but they present different rising times. One of the possible causes of these differences may be an error in some of the parameters involved in the identification such as the convection factor or the dimensions of the coil (mass, volume, etc.). Furthermore, the fact that 4 thermocouples have been used may not be enough to calculate an accurate average temperature.

Although of these inconvinients, the model is accurate enough to proceed with the development of the labs.

4.2.5 Thermal systems lab

Testing of the Thermal Systems Lab was focused on ensuring a smooth completion of the laboratory exercise. Points of interest in testing included the ease of operation of the TOCOM mobile unit, ability to gather relevant data, and clear instructions for calculation of efficiency. Volunteer engineering students were asked to perform the lab by following the directions provided by the lab handout. They were then asked to complete a survey form, tailored to gauge the success of the lab in each of the testing areas (The form is included in the Appendix, Chapter 2). The testable areas are illustrated in Table 4.6.

Customer Requirements	Testing	Evaluation of Results
Thermal systems lab enables students to compare power savings due to recycling loop	Lab test volunteers followed the lab procedure and gave feedback	After revision, 100% of users could complete the lab successfully
Temperature readings before and after addition of heat	Acquisition of temperature measurements of air at source and in controlled space by LabVIEW software	100% of users could take temperature readings using LabVIEW
Ability to measure power provided to fan and heating element	Lab test volunteers gave feedback on success of capture system	100% of users could export the data from LabVIEW
Ability to measure differential	Lab test volunteers gave	After revision,

pressure through the system, and use for mass flow rate calculation	feedback on success of mass flow rate calculation	100% of users correctly calculated the flow rate
Lab exercise can be completed without excessive time to reach temperature set points	Lab test volunteers gave feedback on the length of time required to complete the exercise	Average of 7 minutes to reach
Lab exercise can be completed with only instructions provided by the lab handout	Lab test volunteers gave feedback on successful completion of the exercise	Initial fail, error in equations was revealed, after revision 100% of users could correctly calculate the efficiencies

Table 4.6: Requirements Testing for Thermal Systems Lab.

The design and configuration of the TOCOM Mobile Lab was dependent on the successful integration of the HVAC system and air temperature control system. The thermal systems lab exercise utilizes all three properly integrated subsystems, allowing for the efficiency analysis of both the open and closed system configurations.

Thermocouple sensors were properly installed and interfaced with LabVIEW enabling users to collect and view the temperature measurement data. The reading was initially found to be inaccurate by 3 ºC, but it was calibrated using a thermocouple heat meter. The sensors, one measuring upstream of the heating element and one inside the controlled space, provide a temperature differential which is acquired and recorded by LabVIEW. The

power provided to the system fan and heating element is also recorded in LabVIEW. Upon testing the lab exercise, the users were able to extract all data required for the efficiency analysis.

Mass flow rate of the air through the air temperature control system is calculated from the differential pressure gauge measurement. Though this was possible upon testing the lab, it was discovered that the lab handout did not include the equation for mass flow rate calculation from a pressure differential. This created a problem as the lab exercise could not be completed using only the lab handout as a reference. The necessary corrections were made to the lab handout.

The objective of the thermal systems lab is to compare the performance of the two system configurations by analyzing efficiency. The values of efficiency for some configurations are displayed in Table 4.7.

Set Point	Configuration	Efficiency
27	open	43.60%
27	reheat	53.50%
33	open	62.45%
33	reheat	43.90%

Table 4.7: Efficiency of the air temperature control system

Note that the efficiency decreases for the system with reheat compared to the open system at 33 ºC. This indicates the optimum operating point for the reheat configuration is below 33 ºC. Time to meet these temperature set points was 7 minutes on average, enabling the completion of the lab without excessive downtime.

4.2.6 Controller and sensors

Table 4.8 shows the tests that were conducted on the system. The first test conducted was to make sure that the fire strobe light flashes when the fire pull switch is triggered. This was tested by first examining the program before uploading it to the controller, making sure the correct variables were utilized and that the code was able to be compiled. Then the fire pull switch was triggered by pulling the white lever on the sensor backboard. The test was a success on the first attempt, due to the correct labeling of variables and understanding of code.

Key Customer Requirements	Testing Procedure	Outcome
Fire pull switch enables strobe light	Pulled fire alarm	Pass
Room occupancy wall switch enables fan	Flip wall switch on	Pass
Fire pull switch program disables fan when pulled	Pulled fire alarm	Pass
ATEC moves the damper in the VAV box	Command the ATEC to rotate the damper 50%	Pass
Sensors visible to all users	Multiple people of different heights viewed the system	4/5 people gave passing score

Table 4.8: Controller and Sensor Testing

The room occupancy switch was tested in a very similar manner as the fire pull switch. A program was created that enables the appropriate variable

when the switch on the sensor backboard is triggered. This program is similar to that of the fire pull program so it also worked on first try.

The next test was tougher to get a positive result due to being slightly more complex. The first dozen tests failed due to the code. The variables and installation were all correct, however the code structure was more difficult to understand due to the old FORTRAN based code. The conditional statement had to be aware of multiple scenarios instead of the conventional single scenario. The controller needed to be able to differentiate whether the fan was on when the fire alarm was triggered. In real life situations, if the fire alarm is triggered in a building the system shuts down the HVAC system so that smoke is not distributed throughout the ventilation. After much programming, it became clear that a single multi-conditional statement was all that was needed.

The fourth test was to make sure that the ATEC was correctly installed onto the VAV box and wired to the FLN network to communicate with the main PXC controller. The ATEC has a built in actuator that rotates the damper in the VAV box to limit the airflow. The first test on the device was to make sure the ATEC was able to rotate the damper when given a command from a computer directly plugged into it. After that succeeded, the device was connected to the PXC controller through the FLN network and a command was sent from the desktop computer running Insight instructing the device to rotate the damper 50% (about a 45° angle). This, to some surprise, worked without hesitation, proving the successful installation and networking of the ATEC.

The last test conducted on the system was to make sure users of all heights could easily see all the sensors on the backboard. Five individuals were selected based on a variety of heights (ranging from 5 foot 3 inches to 6 foot 3 inches) and asked to examine the sensor backboard. Four out of the five

people could see all the components on the backboard with ease. One person had a slight difficulty reading the display of the temperature/humidity sensor in the top left corner of the board. Fortunately the values for that sensor can be found in the GUI.

4.2.7 Guide User Interface (GUI)

Customer Requirements	Testing Procedure	Results
Display Temperature, CO2, and Humidity	Observe the displayed results and test with another temperature sensor on separate system to verify results	Pass
Easily Navigable GUI	Distribute a survey to students and team members and receive feedback	90% (18/20)
Switch to Activate VAV system	Turn on switch and see if fan turns on and observe if the values on the GUI reflect this change	Pass
Display Alerts and Alarms	Watch the values exceed the set limit and observe if an alarm is activated	Pass

Table 4.9: Testing Procedure and Results for GUI

The display of temperature and other values are tested by observing if the system is in fact displaying values. To ensure that those values are correct

other separate sensors measure the temperature and the results are compared to verify the correct values. The results show that the system does in fact display the Temperature, CO2, and Humidity values.

The alerts and alarms are tested by making the values exceed the set guidelines for too high and observing if the alarm goes off. The results show that the alerts and displays do in fact alert the user when they get past the set limit off acceptable ranges.

The VAV system turning on by a switch is tested by turning the switch and observing if the system has been turned on. The temperature should change in the GUI when the switch turns on and to be sure that the system is functioning, the display reflects that change in temperature. The results show that the system does in fact respond to the switch when it has been activated.

The GUI itself needs to be user friendly and this is tested by having students and group members work through the GUI and take a survey to express what they liked, disliked, and suggestions for improvement. After students took the survey their results showed that overall the GUI has attained its goal of being easy to navigate and aesthetically pleasing. Some comments about improvement oriented around the need for a Home and Back button on each page, the button layout on the first screen needs to be larger, and the descriptions for parts text needs to be larger. All these suggestions were taken into account and changes to the GUI reflect that input. The surveys were administered on April 30- May 3/2011 to 17 engineering students and 3 non-engineering majors.

References

[1]F.Luis Pagola; *Control Digital*; Universidad Pontificia Comillas.

[2]F.Luis Pagola; Regulación Automática; Universidad Pontificia Comillas.

[3]Frank P.Incropera, David P.De Witt;"Fundamentos de transferencia de calor.

[4] National Instruments; www.ni.com.

[5]Isaac Pérez Moreno; "*Manual de prácticas de control avanzado utilizando la tarjeta de adquisición de datos NI USB 6008".*

[6]Siemens;"APOGEE Actuating Terminal Equipment Controller: owners manual".

[7] Siemens; "Introducing the Zone Control Unit".

PART II

BUDGET

1. Budget

This section includes a detailed budget that has been required to succesfully develop the Project.

Labor budget:

Considering an average engineer's remuneration of $50^{\$}/_{\text{hour}}$ and 300 hours of total work, the final cost is:

$$\text{Total cost} = 50\ {}^{€\$}/_{\text{hour}} \cdot 300\ \text{hour} = 15000\$$$

Hardware:

Tables 1.1 and 1.2 show a detailed part lists of both Siemens and HCAV components with their corresponding prices.

QTY	Product Number	Part Description	Retail Price	Total		Siemens Price
1	PXC100-PE.A	PXC Modular w/FLN & TX-I/O	$7,097.22	$7,097.22		$2,365.74
1	PXX-485.3	Expansion Module, 3 RS-485 Connections	$908.45	$908.45		$302.82
1	TXS1.12FA	24VDC Supply	$560.00	$560.00		$186.67
1	TXM1.16D	16 Digital Input Module	$738.00	$738.00		$246.00
2	TXM1.6R-M	6 Digital Output Relay Module w/OVD	$1,113.89	$2,227.78		$742.59
1	TXM1.8U-ML	8 Universal I/O Module w/OVD & LCD	$1,569.75	$1,569.75		$523.25
2	TXM1.8X-ML	8 Universal I/O Module w/4-20mA, OVD & LCD	$1,847.22	$3,694.44		$1,231.48
1	550-405	Actuating Terminal Equipment Controller (ATEC VAV)	$806.25	$806.25		$268.75
1	540-100	Terminal Equipment Controller (TEC)	$647.95	$647.95		$215.98
1	536-811	100K OHM TEC Thermistor Temperature Sensor	$46.12	$46.12		$15.37
1	540-128	10K OHM TEC Thermistor Temperature Sensor	$50.80	$50.80		$16.93
1	QAM2012.010	Platinum 1K OHM Duct Temperature Sensor	$36.00	$36.00		$12.00
1	533-376-4	20-120°F 100 OHM Duct Temperature Sensor,4-20mA	$155.45	$155.45		$51.82
1	QPA2000	CO2 Room Air Quality Sensor, 0-10V	$672.73	$672.73		$224.24
1	QFA3171D	Room Humidity/Temperature Sensor w/Display, 4-20mA	$750.00	$750.00		$250.00
2	540-680FB	TEC Room Temperature Sensor w/STPT & Display	$177.17	$354.34		$118.11
1	GDE131.1P	Open Air Actuator	$278.22	$278.22		$92.74
1	500-636173	Visual Strobe Light	$69.12	$69.12		$23.04
1	141-0574	Air Flow Switch, .05-1.0 WC	$119.98	$119.98		$39.99
1	3VU69	Dayton AC 239 CFM Axial Fan	$78.30	$78.30		$26.10
5	RH1BU-AC24V	SPDT 24VAC Relay w/base	$4.75	$23.75		$7.92
1	571-010-3P11-USB	Insight Advanced Server 1 User License	$5,000.00	$5,000.00		$1,666.67
1	538-670	Trunk Interface	$806.36	$806.36		$268.79
1		Dell Computer/Monitor	$1,100.00	$1,100.00		$366.67
		Total		$27,791.01		$9,263.67

Table 1.1: Siemens display parts list

1" Inline Electric Valve	3	Orbit	57101	Home Depot	$35.97	
PVC 90 EL	3	Valencia Pipe	1120	Home Depot	$1.71	
1" M Adapter	4	Valencia Pipe	436-010HC	Home Depot	$2.72	
1" Tee SSS	2	Valencia Pipe	401-020HC	Home Depot	$1.14	
ABS Bushing	2	VPC	C5801-2-F	Home Depot	$5.50	
PVC Bushing	2	Valencia Pipe	439-131HC	Home Depot	$1.92	
1" x 2ft PVC	2	Valencia Pipe	2201	Home Depot	$3.34	
3" x 2ft ABS	1	VPC	1202	Home Depot	$7.75	
ABS Coupling	2	VPC	C5801	Home Depot	$3.58	
Turbo Styler	1	Revlon	063-09-0473	Target	$19.99	
Bonding Adhesive	1	Oatey	30812	Home Depot	$7.86	
Electrical Tape	1	Tartan	1710	Home Depot	$0.68	
					$92.16	Total System Cost
1" x 4" x 8'	4	Rancho Cucamunga	-	Home Depot	$17.12	
2" x 6" x 8'	2	Rancho Cucamunga	-	Home Depot	$7.28	
2' x 4' x 5/8" Plywood Panel	1	Boise	1511004	Home Depot	$17.47	
2' x 4' x 1/8" Plywood Panel	1	Boise	103095	Home Depot	$20.80	
36" x 30" Acrylic Sheet	1	Optix	MC-06	Home Depot	$51.76	
1/2 lb Screws	1	Grip-Rite	158CDWS1	Home Depot	$5.94	
2in Steel Screws	1	Grip-Rite	2CDWS5	Home Depot	$5.94	
Bag of 4 Caster Screws	4	Richelieu Hardware	8200	Home Depot	$3.92	
3in Caster Wheel	2	Richelieu Hardware	70721BC	Home Depot	$19.94	
3in Locking Caster Wheel	2	Richelieu Hardware	70722BC	Home Depot	$23.94	
					$174.11	Total System Cost
NI USB-6009 DAQ	4	National Instruments	779026-01	National Instruments	$600	
NI USB-TC01 Thermocouple	3	National Instruments	781314-01	National Instruments	$297.00	
Milwauki Thermocouple	3	Milwaukee	49-77-2002	Tool Barn	$33.00	
					$ 930	Total System Cost

Table 1.2 Parts list for HVAC components

The overall budget in hardware components for the project was $10,193.67. The majority of the funding ($9,263.67) was provided by Siemens Industry which included the computer and the components. USD Associated Students (AS) also provided funding for the construction of the cart and wiring of the HVAC system.

Software

To develope the Project the following programs have been required:

LabVIEW……………………………150$

Matlab with Simulink…………..150$

Microssoft Office 2007…………600$

Final cost=900$

In conclusión, the final budget adding labor, hardware and software is:

$$\text{Final cost} = 900\$ + 10{,}193.67\$ + 15000\$ = 26{,}096.67\$$$

PART III

APPENDIX

Appendix A

Controller/sensors and Guide User Interface appendix

A.1 Controller and Sensors Appendix

Analog Input (AI)	Analog Output (AO)	Digital Input (DI)	Digital Output (DO)
PXC controller has analog inputs to receive signals from analog devices (i.e. sensors)	Temperature, CO2, and Humidity sensors are analog devices that output a linear analog 4mA-20mA or 0V-10V signal	PXC controller has dry contact digital inputs that detect if the circuit is completed from one contact to the other	Buttons and switches output a dry contact digital signal when pressed or flipped. PXC controller has digital outputs for ON/OFF operation an enable relays

Table 1.1 Description of inputs and outputs

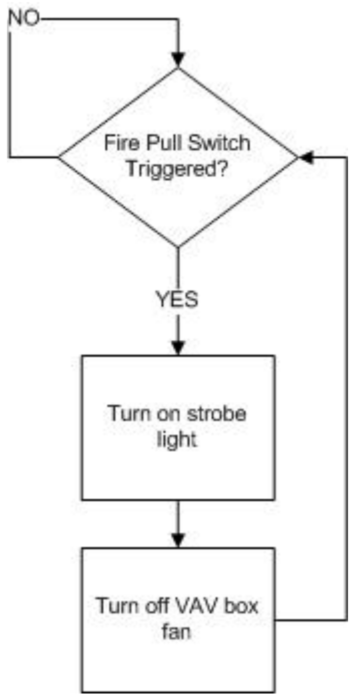


Figure 1.1: Fire Pull Switch Program Flowchart

This program represents what happens when a real wall mounted fire pull station is triggered in a building. When the alarm is triggered, a strobe light will flash, and an alarm is displayed in the Insight software.

Point Declaration	Type	Description
TCM.SWT.01.FIRE	LDI	FIRE PULL SWITCH
TCM.ALM.01.FIRE	LDO	FIRE ALARM LIGHT/SIREN

```
00010   C
00020   C ---FIRE PULL ALARM---
00030   C
00040   DEFINE(FIRE,"TCM.SWT.01.FIRE")
00050   DEFINE(ALFIRE,"TCM.ALM.01.FIRE")
00060   IF(%FIRE%.EQ.OFF) THEN OFF(%ALFIRE%) ELSE ON(%ALFIRE%)
```

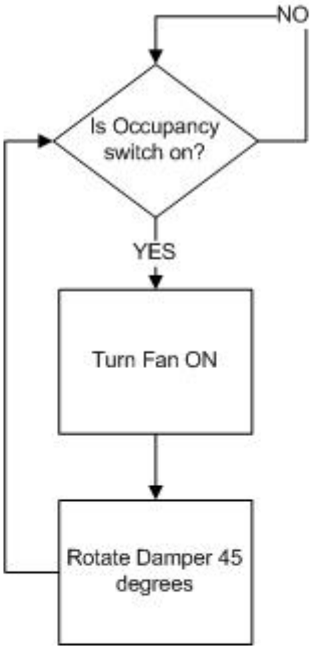


Figure 1.2 Occupancy Switch Program Flowchart

This program detects occupancy. In order for the system to be used, a switch will need to be flipped (as if a person was to walk into a room or office). When a person enables the occupancy switch, the fan in the VAV box turns on and the model damper starts rotating to simulate the HVAC system responding the environment. If the Fire Alarm is enabled, then the fan shuts off to prevent smoke circulation.

Point Declaration	Type	Description
TCM.AH1.01.DMPR	LAO	MODEL AIR HANDLING DAMPER
TCM.SWT.02.OCPY	LDI	OCCUPANCY SWITCH
TCM.VAV.01.FAN	LDO	VAV BOX FAN

```
00070  C
00080  C ---OCCUPANCY SWITCH---
00090  C
00100  DEFINE(DMPR,"TCM.VAV.02.DMPR")   ---Define Variables, variables called in
       other programs do not need to be called again (i.e. FIRE)
00110  DEFINE(OCPY,"TCM.SWT.02.OCPY")
00120  DEFINE(FAN,"TCM.VAV.01.FAN")
00140
       IF(%OCPY%.EQ.OFF.AND.%FIRE%.EQ.OFF).OR.(%OCPY%.EQ.ON.AND.%FIRE%.EQ.
       ON).OR.(%OCPY%.EQ.OFF.AND.%FIRE%.EQ. ON) THEN OFF(%FAN%)ELSE
       ON(%FAN%)
```

A.2 Guide User Interface (GUI) Appendix

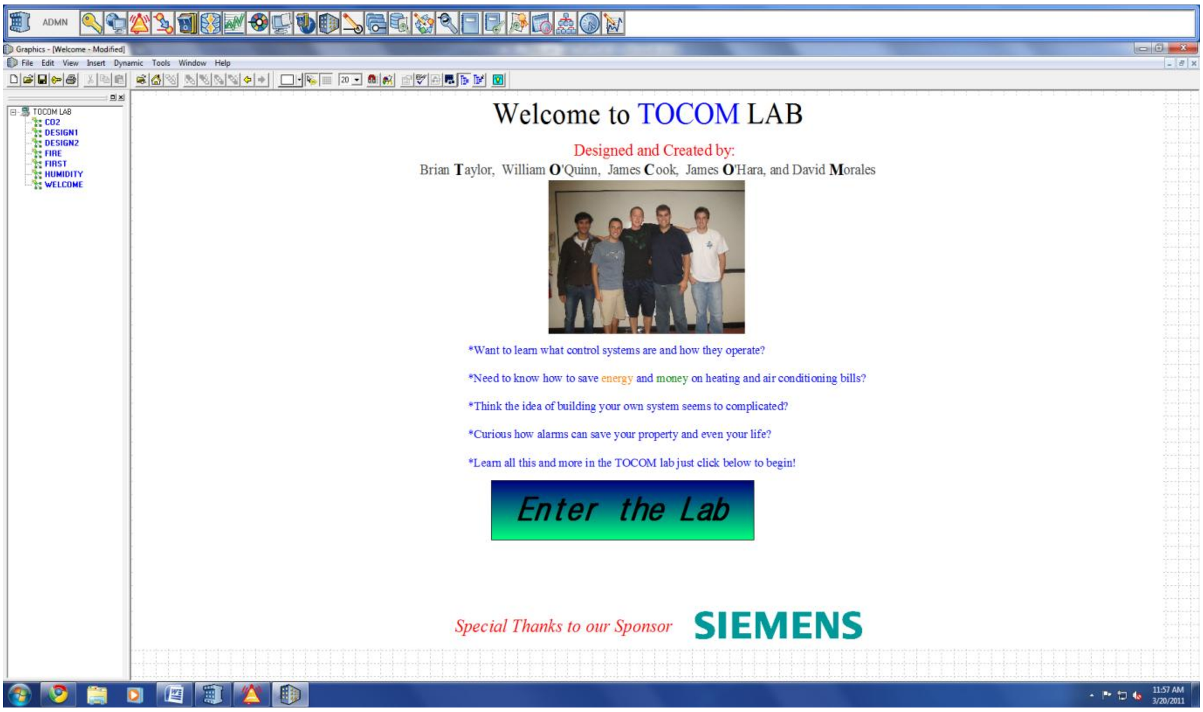


Figure 1.3: GUI Homepage

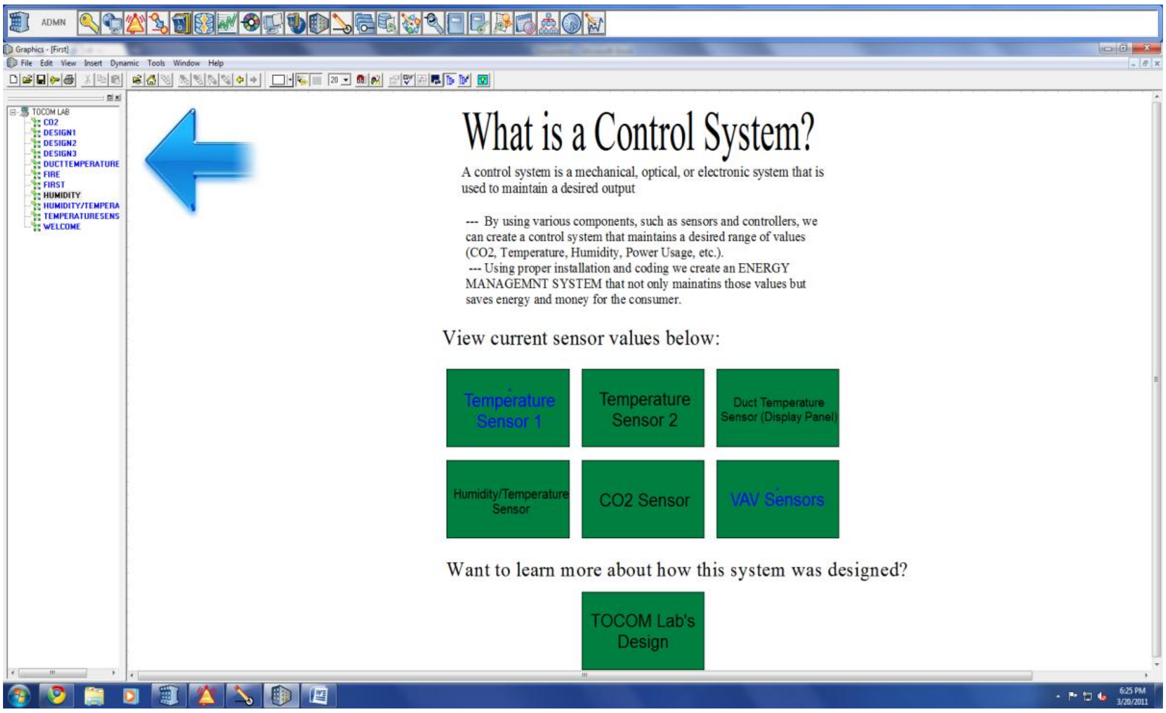


Figure 1.4: First Page

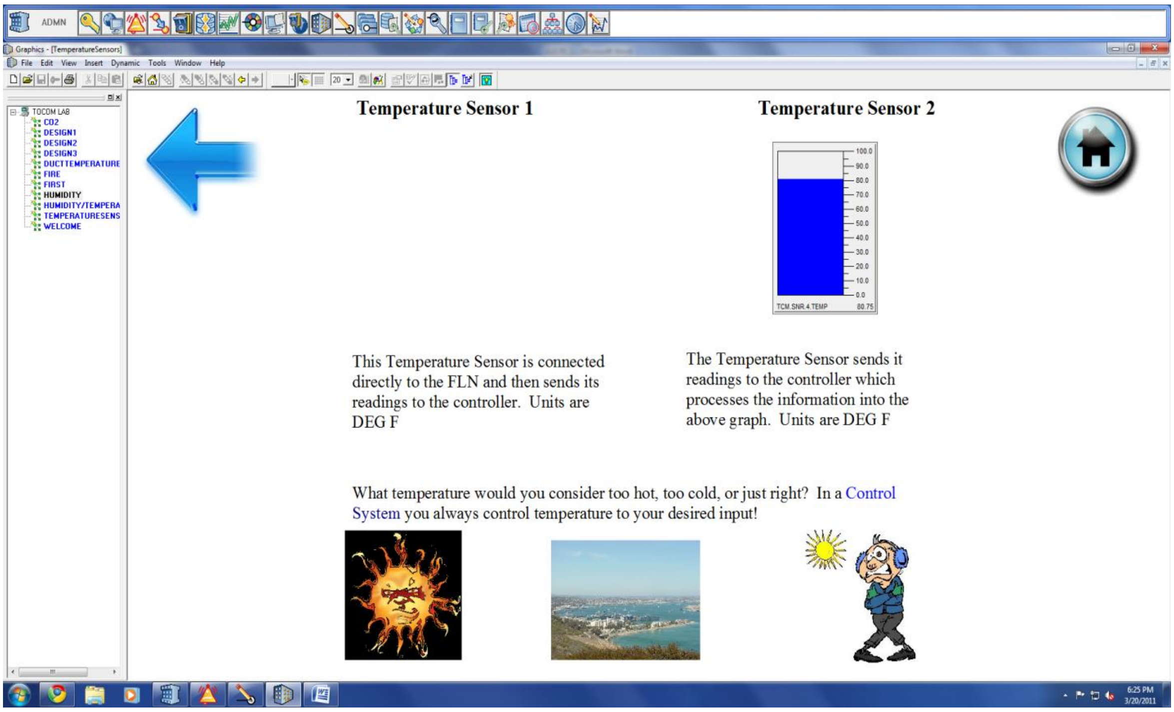


Figure 1.5: Temperature Sensors Page

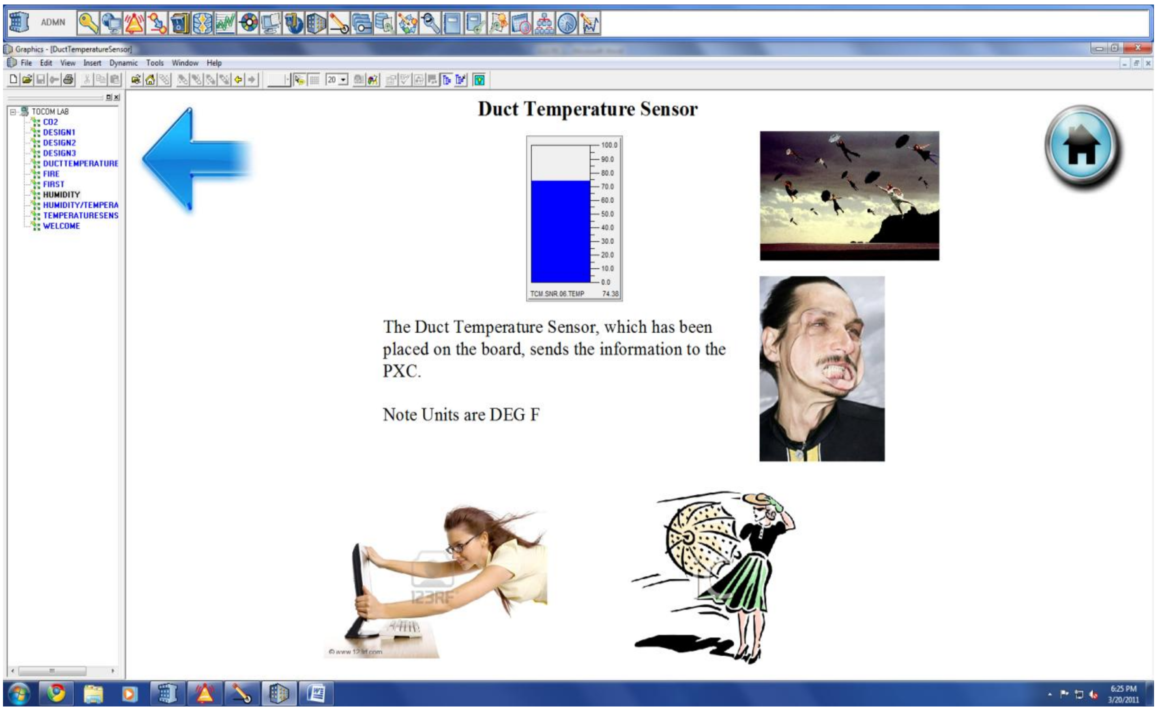


Figure 1.6: Duct Temperature Sensor Page

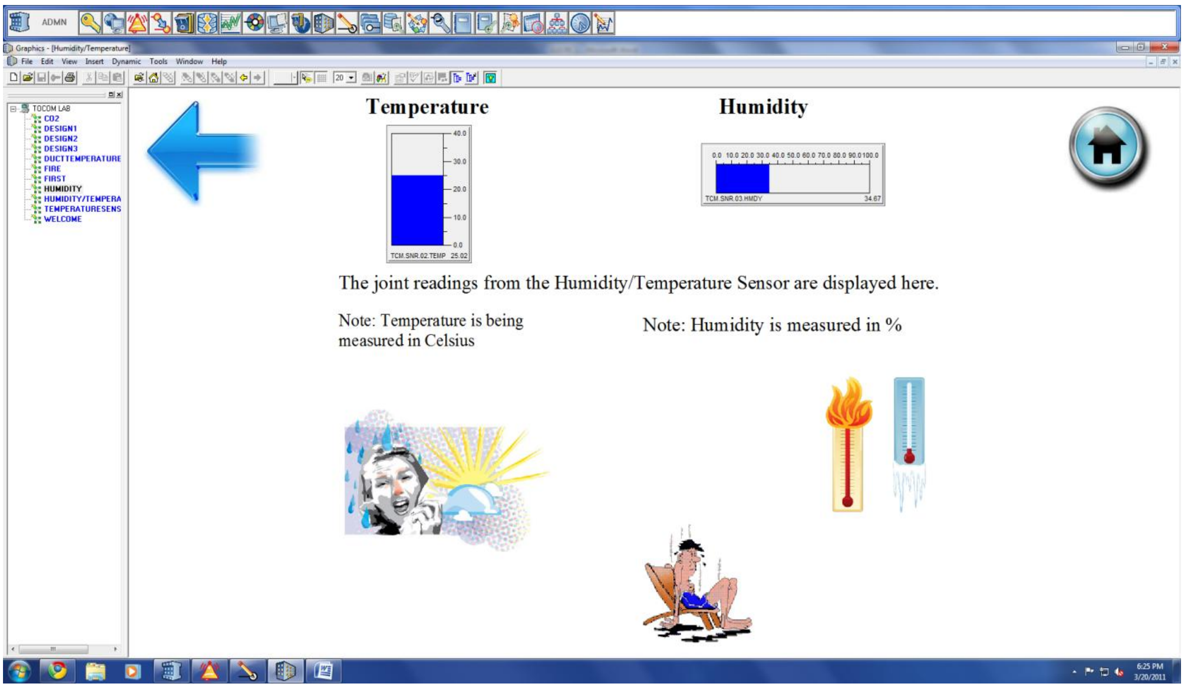


Figure 1.7: Humidity/Temperature Readings

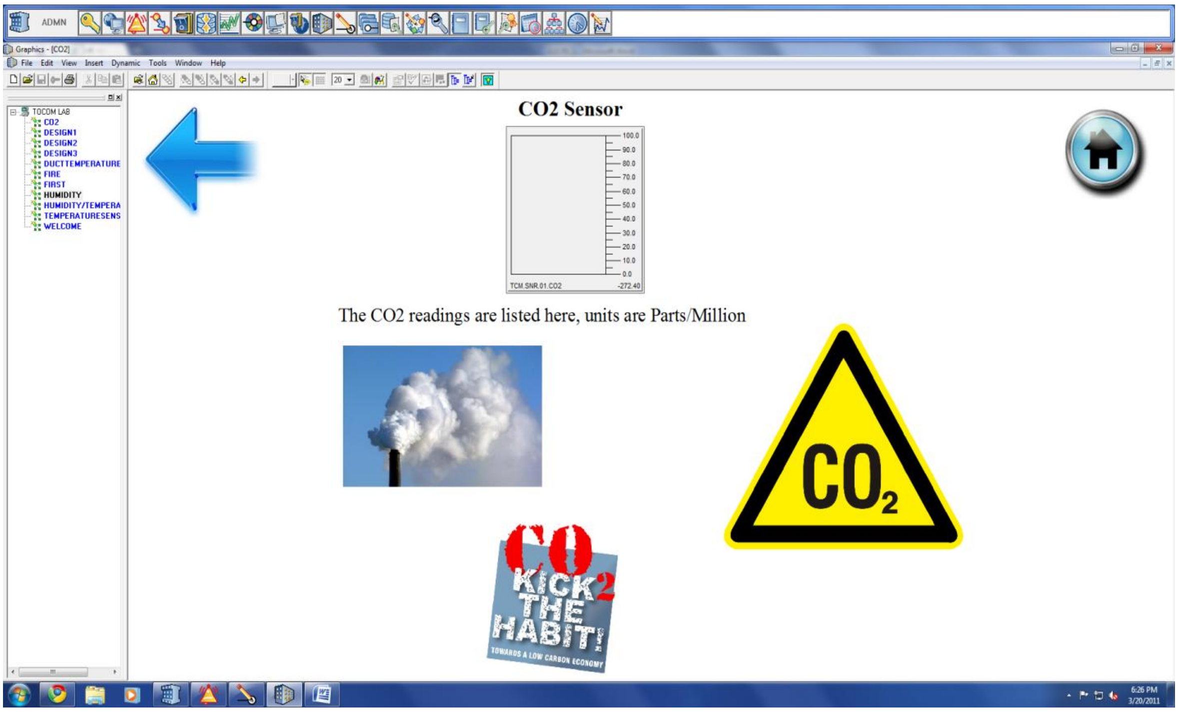


Figure 1.8: CO2 Sensor Page

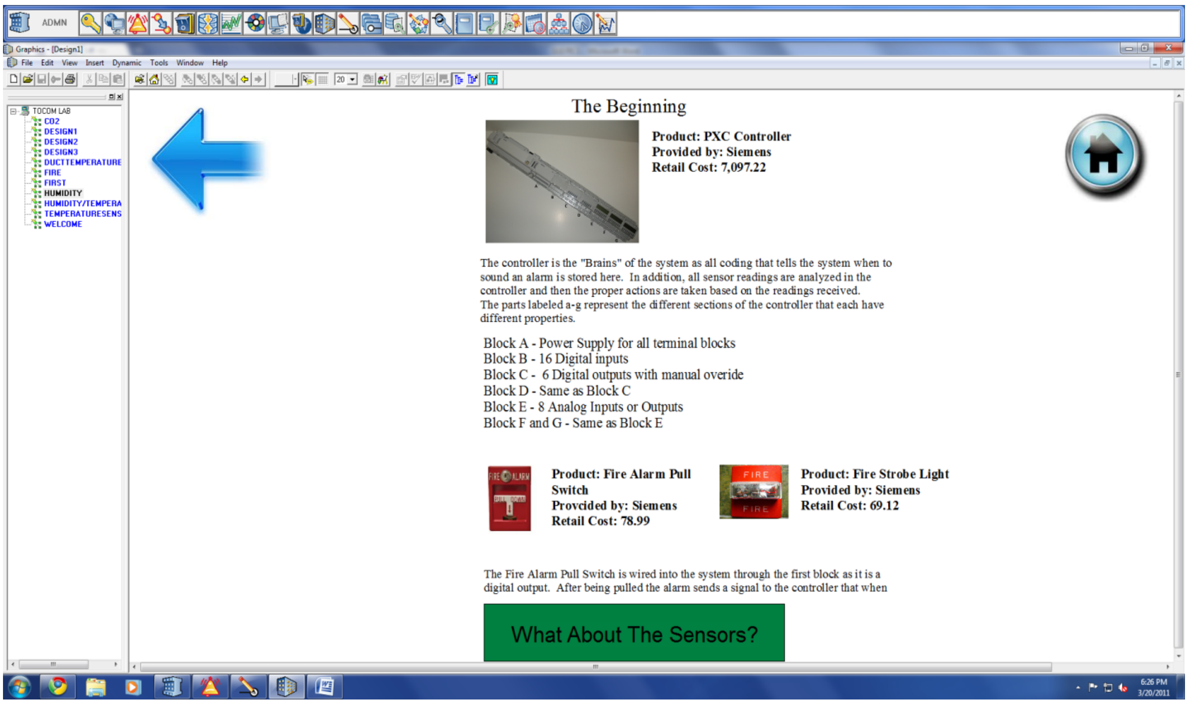


Figure 1.9: Beginning Page

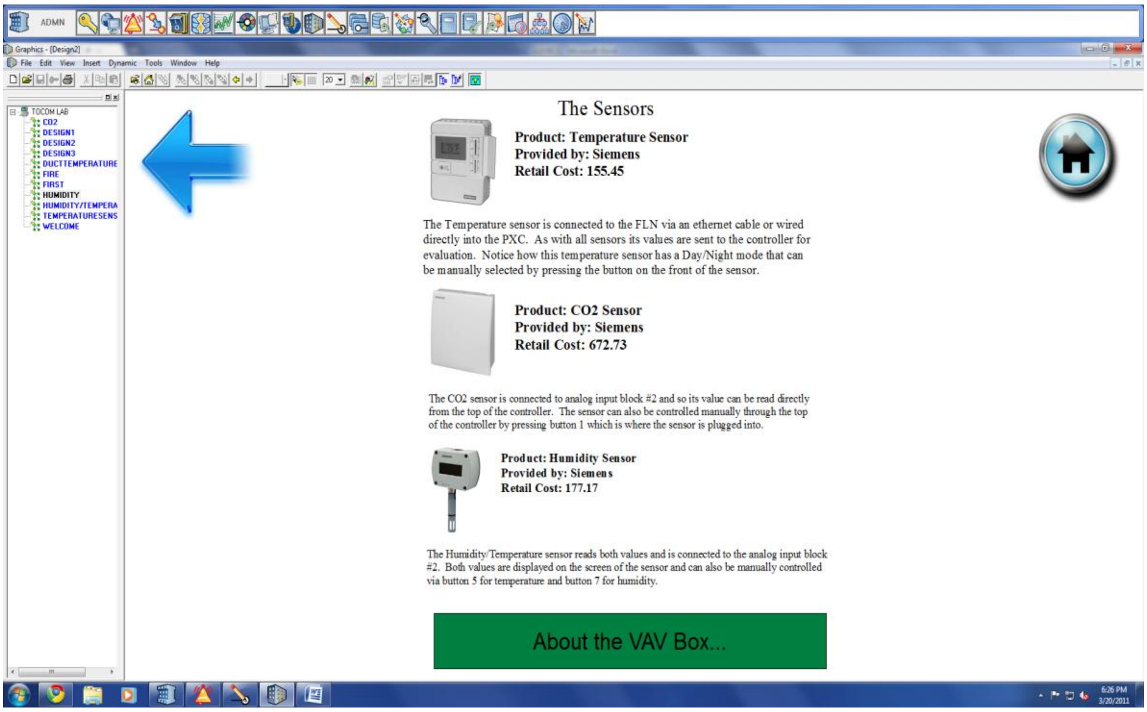


Figure 1.10: Design Page 2

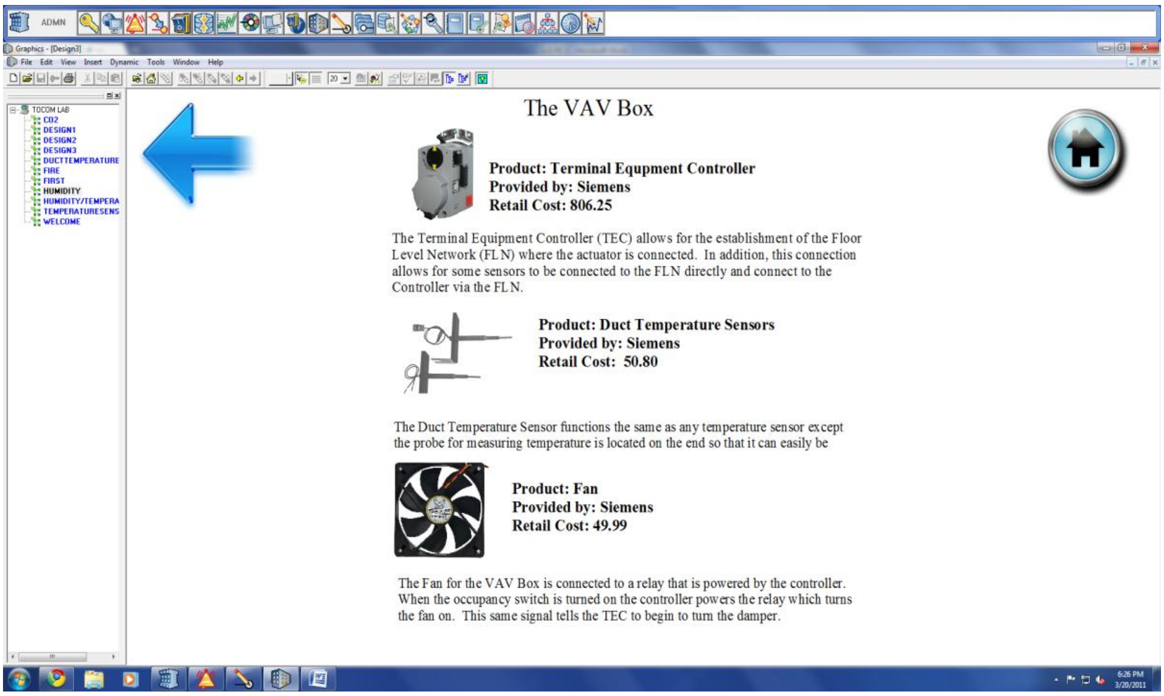


Figure 1.11 Design Page 3

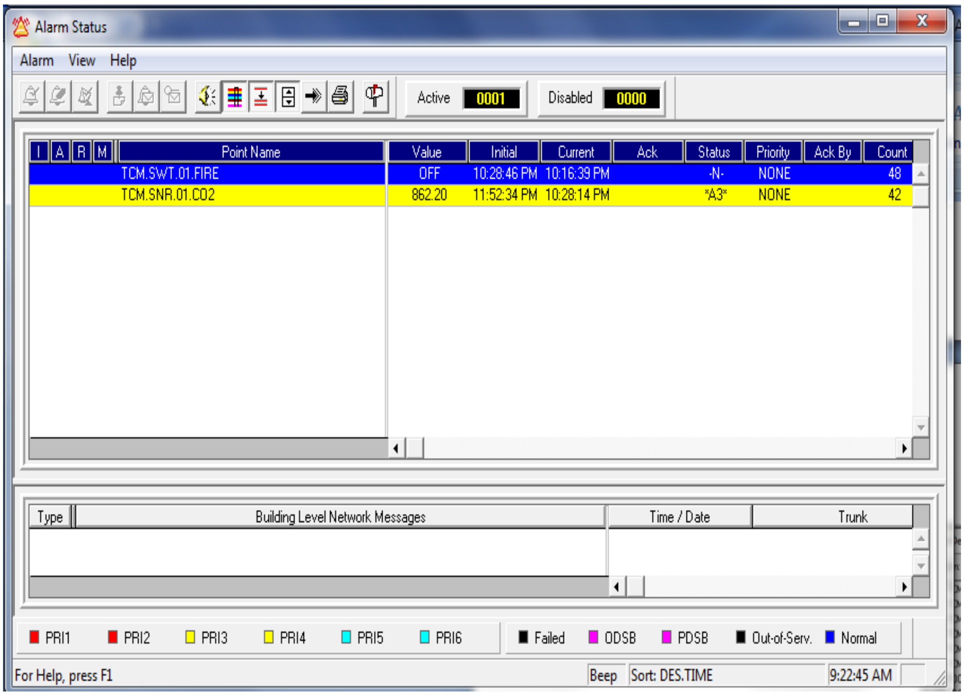


Figure 1.12: Alarm page

Appendix B: Thermal Systems Lab users manual.

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1.Introduction

The TOCOM Mobile Lab unit uses LabVIEW to run a control system which regulates the air temperature in an enclosed environment. In the following experiments the air temperature control system will be used to provide a steady state temperature within the enclosed environment.

Increased efficiency is a primary motivation for many engineering applications. By taking temperature, differential pressure, and electrical power measurements the efficiency of the air temperature control system can be calculated. The objective of the following experiment is to analyze and compare the efficiency of (1) an open loop heating system (2) as well as a heating system using reheat, or a recirculation of the heated air through the system.

2. Equipment Description:

The air temperature control system is physically composed of the enclosed environment and the HVAC System (seen in Figure 1).

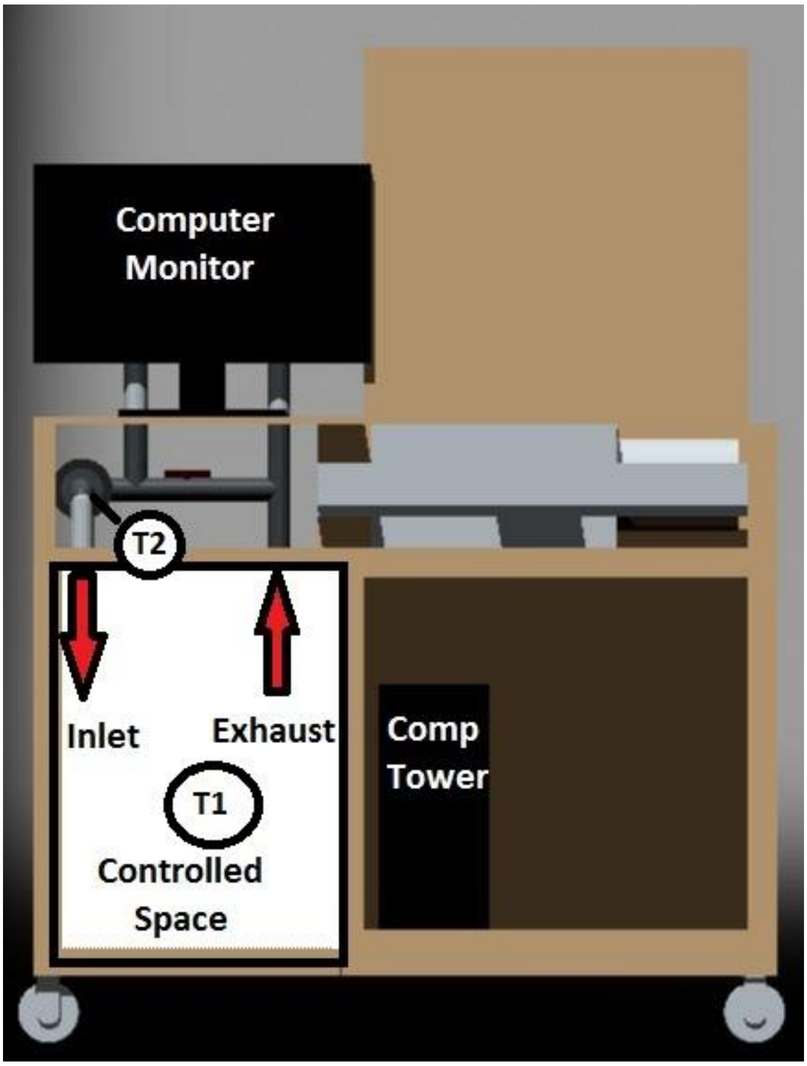


Figure 1 – HVAC System diagram

The control system allows the system devices (fan motor and electric resistive heating coil within the HVAC loop) to be activated and configured through the LabVIEW software. Temperature data will be collected via thermocouple sensors placed throughout the system and displayed through

LabVIEW. A detailed diagram of the airflow and devices within the system can be seen in Figure 2. T1 and T2 indicate the placement of the controlled space temperature and inlet temperature respectively.

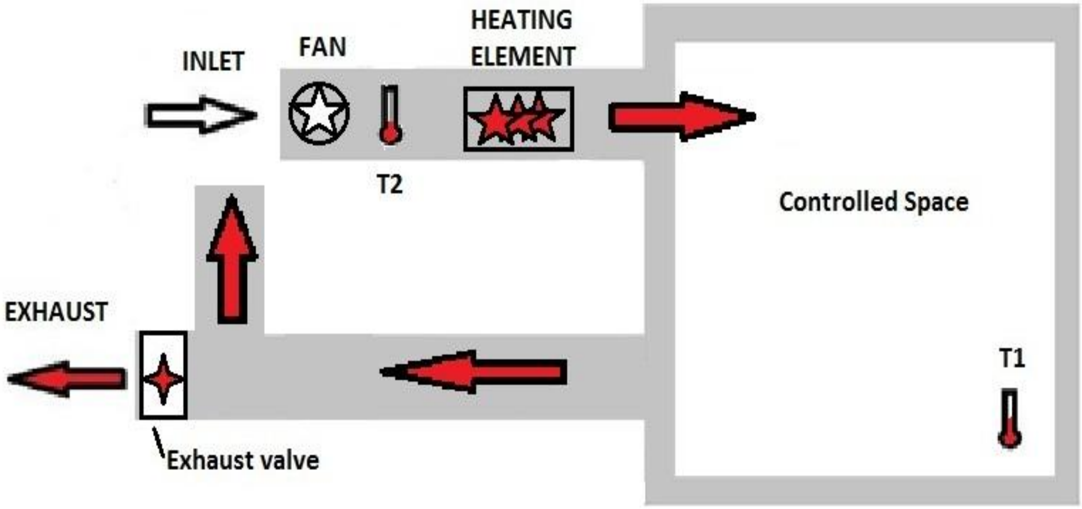


Figure 2 - HVAC circuit diagram

The valves can be set to two positions which change the system geometry from (1) open without reheat to (2) open with reheat. By closing the reheat valve, the system changes from configuration (1) to (2). The reheat system valve configuration is shown in Figure 3.

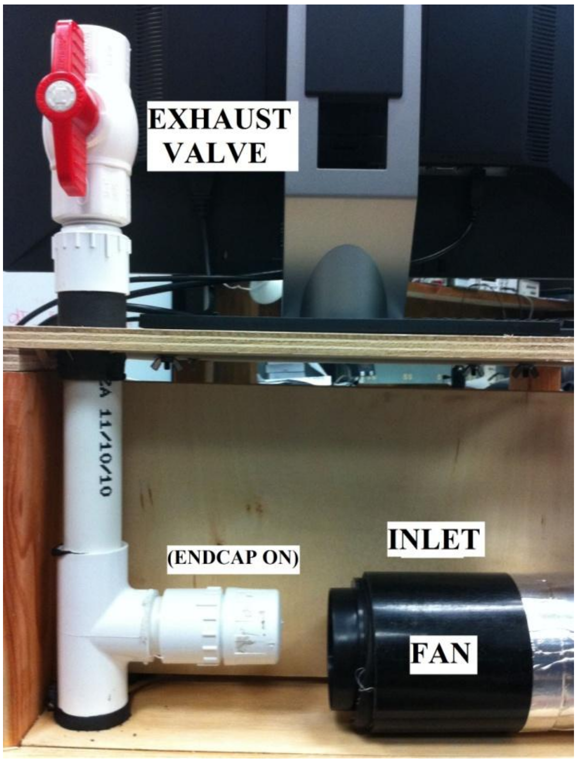


Figure 3 - Open valve configuration

Pressure is measured via a differential pressure gauge, which compares the stagnation pressure and dynamic pressure of the air moving through the inlet to the controlled space (see Figure 4).

Figure 4 – Differential pressure gauge

3. Nomenclature:

Quantity	Symbol	Units (SI)	Units (Imperial)	Description
Current	I	A	-	flow of electric charge
Voltage	V	V	-	electrical potential difference
Power	P	W	-	rate of energy transfer
Pressure	p	(Pa) N/m^2	inch WC	force exerted on a container per unit area
Volumetric Flow Rate	Ꝟ	m^3/s	ft^3/s	volume which passes through pipe per unit time
Mass Flow rate	m	kg/s	slugs/s	rate mass passes through pipe per unit time
Density	ρ	kg/m^3	slugs/ft^3	mass per unit volume
Efficiency	η	%	%	percentage of power retained from input to outp⍰t
Specific heat	c	(kJ/kg)K	(Btu/lb)^{0}R	amount of heat required to change temperature
Temperature	T	K	^{0}R	physical property of matter relating to thermal equilibrium
Heat transfer	$\dot{Q}$	kJ/kg	Btu/lb	rate of heat transfer per unit mass
		kJ/s	Btu/s	rate of h⍰at transfer per unit time
Enthalpy	h	kJ/kg	Btu/lb	total energy of a thermodynamic system

4. Investigation of air temperature control system

Objective:

To determine the efficiency of the system at steady state by comparing power input to heat output, and to compare the efficiency of the reheat configuration to the open loop configuration.

Theory:

Efficiency of the heating system can be described by EQ. 1:

$$\eta = \frac{Q_{out}}{P_{in}} \qquad \text{- EQ. 1}$$

In this case, the ‘Qout’ is the rate of heat transferred to the air by the HVAC system. The ‘Pin’ is the electrical power added to the fan and resistive heating coil. The total electrical power can be calculated with EQ. 2.

$$P_{total} = P_{coil} + P_{fan} \qquad \text{- EQ. 2}$$

The rate of heat added to the air in the system can be expressed by EQ. 3.

$$\dot{Q} = \dot{m} \cdot \Delta h \qquad \text{- EQ. 3}$$

Mass flow rate can be calculated using differential pressure and some system performance dependent constants. The calculation can be performed directly using EQ. 4.

$$\dot{m} = \sqrt{(\Delta p \cdot (72 \times 10^{-6})}$$

- EQ. 4

where Δp is the differential pressure (inches W.C.). The mass flow rate is in SI units ($\frac{kg}{s}$).

If the assumption is made that the air in the system is incompressible and can be modeled as an ideal gas, the relationship described in EQ. 5 can be used. This assumption is appropriate for this system’s analysis.

$$\Delta h \approx c \cdot \Delta T \qquad \text{- EQ. 5}$$

By substituting EQ. 2, 3, 4, and 5 into EQ. 1 we find the equation for efficiency described in EQ. 6.

$$\eta = \frac{\dot{m} \cdot c \cdot \Delta T}{P_{total}} \qquad \text{- EQ. 6}$$

Method:

4.1 Part A – Investigation of air heating system

Ensure the system geometry is in the open configuration by checking that the exhaust valve is open and the end cap is placed on the reheat outlet (see Figure 5).

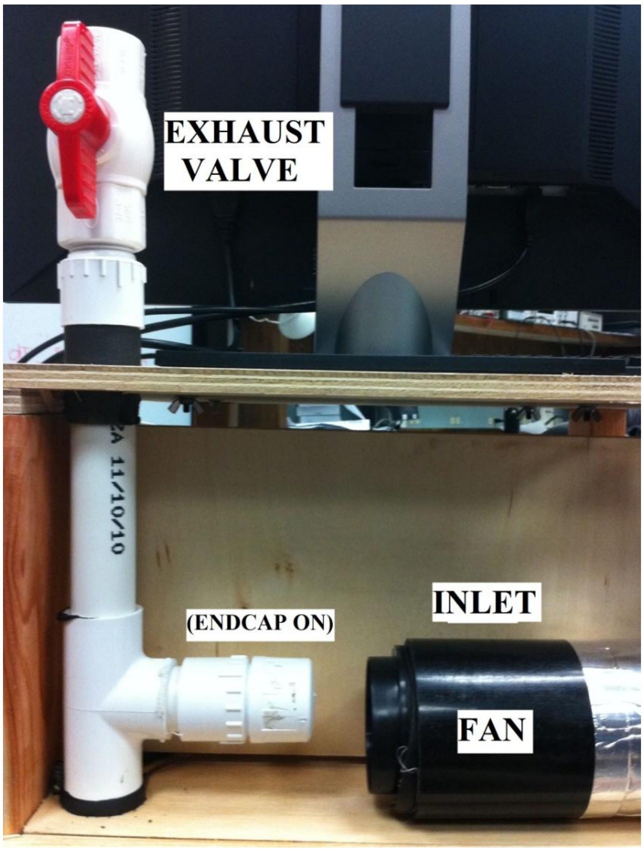


Figure 5 - Open System Valve Configuration

Check that power is supplied to the HVAC loop by ensuring the onboard power strip is switched to the on position. Turn on the computer aboard the TOCOM Mobile Unit and open the control system in LabVIEW by opening the VI file via the following path:

Desktop >> TOCOM >> control_PID tocomlab.vi

Open the Thermal Systems tab to open the interface shown in Figure 6. This interface will be used to activate the control system and simultaneously monitor the instantaneous temperature and power measurements.

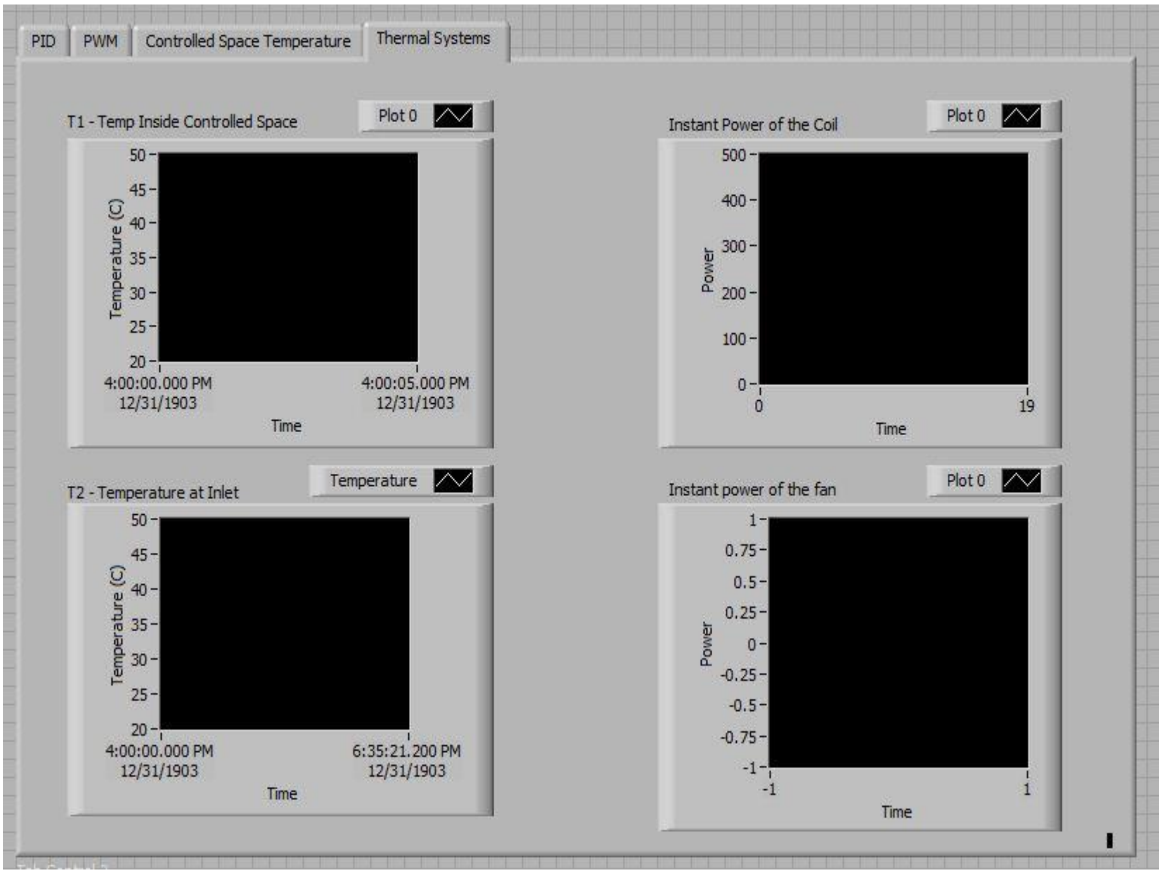


Figure 6 - Screenshot of LabVIEW interface

The control system which provides the steady-state temperature within the system must be configured before beginning the experiment:

Under the PID tab, enter the following values in their respective fields:

Kp=10

Ki=0.1

Kd=0.01

Under the PWM tab, enter the values in their respective fields:

Precision = 25

Rate Time = 5

Amplitude = 5

In LabVIEW under the PID tab, change the temperature set point (desired_temp) to 28 ºC. Enable the control system by clicking the left pointing arrow icon in the top left corner of the LabVIEW window. Allow the system to reach steady-state temperature; this will be evident by a flat trend in the temperature display (under Thermal Systems tab). Here the control system will maintain the temperature in the controlled space by intermittently actuating the heating coil. The fan should always be running.

While the enclosed space is being heated, record the pressure reading from the differential pressure gauge within the controlled space, visible through the controlled space window.

Once the temperature set point has been reached and the system is at steady state (seen in Figure 7), use LabVIEW to collect temperature readings from both the controlled space (T1), the air inlet (T2), and power supplied to the fan and heating coil (note that for part A the inlet temperature T2 will be room temperature).

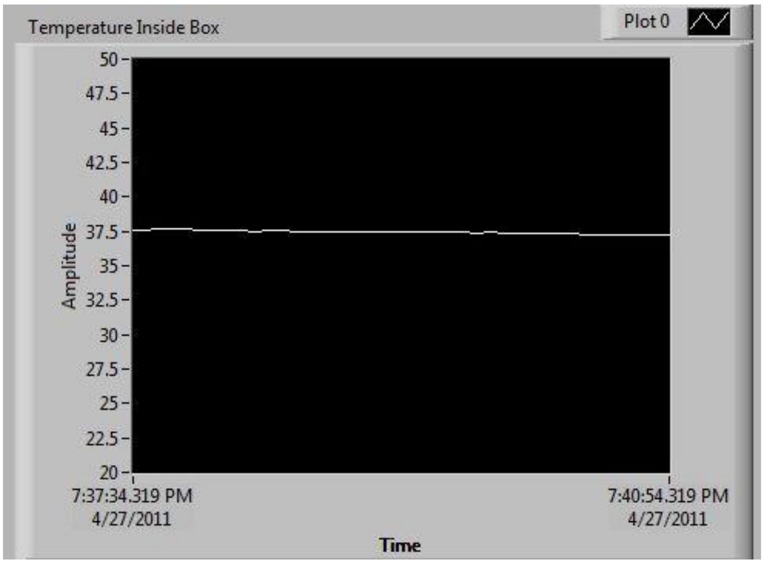


Figure 7 - Steady-state reading in LabVIEW

Measurements are displayed within the Thermal Systems tab, and can be exported to Excel after the program has stopped running. Before collecting data be sure to clear the current data by right-clicking each graph and selecting 'clear chart'. After sufficient data has been collected, stop operation of the system by clicking the 'stop process' button. To extract data right-click the graph displaying the desired data, select 'Export', then 'Export Data to Excel'. Excel will automatically open with the data displayed.

Collect data points for each temperature set point at 28, 30, and 33^{0}C (note that the room temperature affects the speed to reach the set point).

4.2 Part B – Investigation of reheat loop in air heating system

Close the exhaust valve and remove the end cap. The system geometry is now in the reheat configuration. The valve configuration for the closed system is shown in Figure 8.

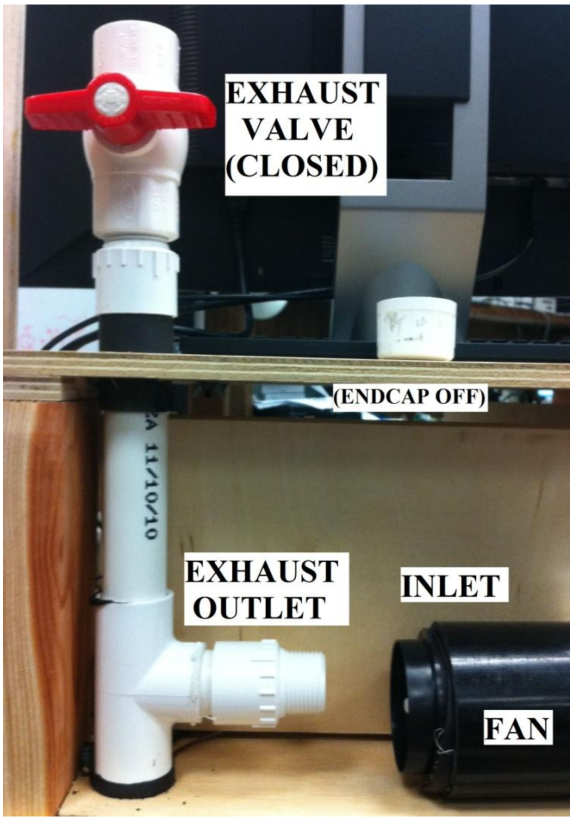


Figure 8 - Closed System Valve Configuration

Repeat Part A with the closed configuration of the HVAC loop.

4.3 Results:

Results for the collected data should be recorded in a table like the one shown below:

Trial	T1	T2	ΔT (T1-T2)	Δh	Δp	ṁ	Q̇in	Pin	η
#	^{0}C	^{0}C	K	kJ/kg	inch WC	kg/s	kJ/kg	kW	%

For near room temperature air consider the following constant:

c = 1.005 (kJ/kg) ^{0}K, and ρ = 1.1614 kg/m3.

Note that the specific heat of air and density required for the calculation is assumed to be constant due to the relatively small change in temperature.

Recall that 1 kJ/s = 1 kW.

4.4 Conclusion:

Compare the efficiencies from Experiment A with those from experiment B. Comment on the cause of any differences between the two data sets.

5. Experimenter Check List (Procedural Outline)

I. Part A – Investigation of air heating system
   a. Constant values
      i. Power for the fan (provided in LabVIEW)
      ii. T2 – Temperature at inlet (room temperature)
      iii. Differential pressure, can be viewed through window to controlled space
   b. Steady-state values to collect
      i. T1 – Temperature in the controlled space
         1. Use average value of data collected for calculations
         2. Should be fairly constant for steady-state
      ii. Power used by heating coil, use average value of data collected for calculations
   c. Calculate efficiency with the equations provided

II. Part B – Investigation of reheat in air heating system
   a. Constant values
      i. Power for fan (provided in LabVIEW)
      ii. Differential pressure, can be viewed through window to controlled space
   b. Steady-state values to collect
      i. T1 – Temperature in the controlled space
         1. Use average value of data collected for calculations
         2. Should be fairly constant for steady-state
      ii. T2 – Temperature at the inlet
         1. Mix of exhausting room air with room air
         2. Should be a fairly constant, median value
      iii. Power used by heating coil, use average value of data collected for calculations
   c. Calculate efficiency with the equations provided

5.1 Thermal Systems Lab Survey Form

TOCOM Mobile Lab

Thermal Systems Lab Survey Form

Answer the following questions regarding your analysis.

Final efficiency for open system without reheat: ___________________________________

Final efficiency for system with reheat: ____

Please answer the following statements (yes/no).

Were you able to gather all of the required data? If not what data was not collected? ________

Approximately how long did it take for you to complete the lab? ______________________

Please individually rank the following statements (5 – Highest to 1 – Lowest):

Based on your background you are prepared to complete an efficiency analysis of a thermal system.

5 4 3 2 1

The lab handout was easy to follow.

5 4 3 2 1

The lab handout contained all necessary information.

5 4 3 2 1

The user interface facilitated data collection and observation.

5 4 3 2 1

The mobile lab is a useful tool for studying thermal systems.

5 4 3 2 1

Appendix C: Controls system lab users manual.

C.1 Users manual

1. Objectives

The main goal of this lab is to provide a tool that enables students to compare the time response and behavior of a real HVAC system and the corresponding simulation.

To accomplish this objective the student will go through the entire process of controllers design: start from a non linear system, obtain the equivalent linear model (transfer function) and final design of Proportional-Integrative-Derivative (PID) controller.

Finally, the results obtained will be exported to LabVIEW to run the real system.

2. Lab work:

- **A. Plant identification**

1. Run initial_parameters.m and run linearization.mdl. This file gathers the input and output at the operating point.
2. Run prep_adjust. m and select clicking twice the step that is going to be identified.
3. Run adjust.m and get the transfer function.

- **B. Design of PID controller**

1. Open design_PID.m and introduce the transfer function obtained which is named as 'p'.
2. Choose appropriate parameters for the PID: filter factor, margin phase, differential factor, integrative factor. Run the file and get the transfer function and parameters for the PID. This file is based on the Newton Raphson algorithm and provides the optimum parameters.
3. Open PID_test that includes the whole control system in Simulink: Change the parameters (proportional, derivative and integral) and assess the effects they produce in the response.
4. Get the parameters for a time response with 20% overshoot, 50 º of margin phase and the quickest rising time.

- **C. Running the real system**

Using one of the parameters obtained in Step B export them to the LabVIEW interface and run the system. Compare the outcomes with the Matlab simulation under the same conditions, do they match? Why?

C.2 Programs

Program "prep_adjust.m"

```
%%%%% Program to prepare data before algorithm application%%%%%

ts=1;
plot(presion(:,2))

% Clicking two times, the time range we want is defined
[aux1,aux2]=ginput(2);
aux1=ceil(aux1);

%the time range is shifted to zero
time=presion(aux1(1):aux1(2),1)-presion(aux1(1),1);
```

```
tfin=time(end); % end time of the simulation

% We pick out the interval of time desired
presionf=presion(aux1(1):aux1(2),2);
combustiblef=combustible(aux1(1):aux1(2),2);


% Initial levels
presion_0=mean(presion(aux1(1),2));
combustible_0=mean(combustible(aux1(1),2));


% Input and output are set
ent=combustiblef-combustible_0;
sal=presionf-presion_0;
```

Program "adjust.m"

```
ALGORITH SYSTEM ADJUST ALGORITH BASED ON MINMUM QUADRATIC ERROR

%clear all
clear theta thaux dgn J
format compact
format short e


%%%%%%%%   PARAMETERS AND INITIAL VALUES %%%%%%%%%%%%%%%%%%

th=[2.7192e-001  1.0516e+002];%INITIAL VALUES
theta=th;
Np=length(theta);% NUMBER OF PARAMETERS



%%%%%%%%%%%%   PARAMETERS OF THE ALGORITHM
tfin=length(time)-1;
Tsamp=ts;
Nd=tfin/Tsamp;
tol1=1;
tol2=1;
V=1;
Vaux=0.01;
dgn=ones(1,Np);
niter=0;


%%%%%%%%%%%%%%%%%%%%%%%   ALGORITHM
```

```
while (100*(V-Vaux)/Vaux>tol1 | 100*max(abs(dgn./theta))>tol2) %&
niter<10

    niter=niter+1;  % ITERATIONS INCREASED
    % parameters updating
    th=theta;
    %h0=theta(2);

   % sistem simulation
   sim('sistema',tfin);
   %ys=[y(:);y1(:);y2(:)];
   ys=y(:);
   %ym=[sal(:);sal1(:);sal2(:)];
   ym=sal(:);
   error=ys-ym;

    % target function
    V=sqrt(sum((error).^2)/Nd);


    % building of jacobian matrix

    for i=1:Np

        thaux=theta;
        h=.001*abs(theta(i)); % Incremento para las derivadas
        if abs(theta(i))<10*sqrt(eps)
            h=.01*sqrt(eps);
        end
        thaux(i)=theta(i)+h;

        % parameters updating
        th=thaux;
        %h0=thaux(2);

    sim('sistema',tfin);
    %yaux=[y(:);y1(:);y2(:)];
    yaux=y(:);
    %ym=[sal(:);sal1(:);sal2(:)];
    ym=sal(:);
    error=yaux-ym;

        J(:,i)=(yaux-ys)/h;

    end

    % Graphic representation de 'ys', 'ym' and error=ys-ym
    clf
```

```
    stairs([ym ys error])
    grid
    %disp('PAUSE')
    %pause
    %disp('VALE')

    dgn=(J\(ym-ys))'; %

    mu=2;
    Vaux=V+10;
    stb=1;

        while Vaux > V | stb==0

        mu=mu/2;
        thaux=theta+mu*dgn;

        % regulator parameters updating
        th=thaux;
        %h0=thaux(2);

      % State system matrix (linearization)
        [A,B,C,D]=linmod('sistema');
        stb=all(real(eig(A))<=0);

       % Simulation with new parameters
        if stb==0
          yaux=zeros(size(yaux));
       else
       sim('sistema',tfin);
        %yaux=[y(:);y1(:);y2(:)];
        yaux=y(:);
        %ym=[sal(:);sal1(:);sal2(:)];
        ym=sal(:);
        error=yaux-ym;
       end

        Vaux=stb*sqrt(sum((yaux-ym).^2)/Nd);

    end

    % Parameters and target function outputs
    theta=thaux;
    thetha_parameters=[theta]
        Vaux

end
    num=[th(1)];
    den=[th(2) 1];
    plant_tf=tf(num,den)
    p=plant_tf;
```

Program “design_PID.m”

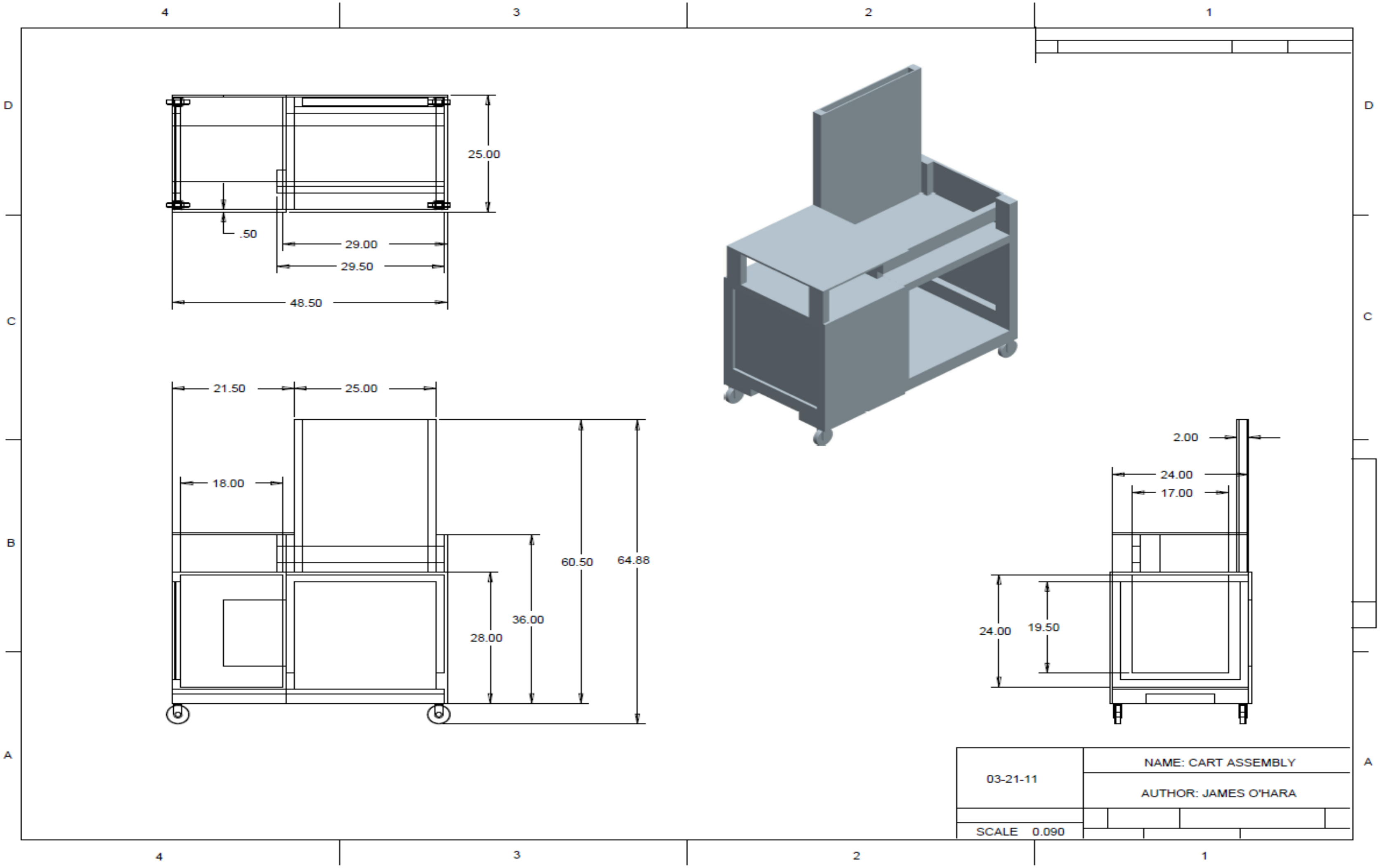
```
% [control,w0]=dis_afpi(p,Mf,Fa,Fr,fa,sol,wmin,wmax)
% control: Transfer function of the final controller.
% w0: cross frecuency
% p: transfer function of the plant
% Mf: Phase margin(grades)
% Fa: Phase advance(grades). Differential part
% Fr: Phase delay(grades,positive) Integral part
% fa : Filter coefficient
% sol: 0 (maximun K) y 1 (minimum K)
% wmin: Starting point to look for the w0
% wmax:Maximun point for w0


% Design parameters
Mf=130;
Fa=10;
Fr=5;
fa=0.1;
wmin=0.000001;
wmax=100000;


aux1=mod(180/pi*angle(freqresp(p,wmin)),-360)+180+Fa-Fr-Mf;
aux2=mod(180/pi*angle(freqresp(p,wmax)),-360)+180+Fa-Fr-Mf;
sol=1;

if (aux1*aux2)>=0
   disp('It does not exist solution for the interval specified')
   control=[];
   w0=[];
   return
end

if (Fa>asin((1-fa)/(1+fa))*180/pi)
   fprintf('The phase advance value must be less than %f',asin((1-
fa)/(1+fa))*180/pi)
   control=[];
   w0=[];
   return
end

while (wmax-wmin)>1e-5
   wmed=(wmin+wmax)/2;
   aux0=mod(180/pi*angle(freqresp(p,wmed)),-360)+180+Fa-Fr-Mf;
   if aux0*aux1<=0
      wmax=wmed;
   else
      wmin=wmed;
   end
end
```

```
% Control AFPI (C(s)=K*(1+Ta*s)*(1+Ti*s)/(1+Ta*fa*s))/s
w0=wmed
C=1/abs(freqresp(p,w0)); %Plant's modulus

if sol==0
   x=(1-fa)/2/tan(Fa*pi/180)+sqrt(((1-fa)/2/tan(Fa*pi/180))^2-fa);
else
    %x=(1-fa)/2/tan(Fa*pi/180)-sqrt(((1-fa)/2/tan(Fa*pi/180))^2-
fa)
x1=((1/fa)-1)/(2*tan(Fa*pi/180))-sqrt((((1/fa)-
1)/(2*tan(Fa*pi/180)))^2-1/fa);
end

Ti=(1/w0)*tan((90-Fr)*pi/180); %Pi value with -5
Ca=C*w0/sqrt(1+(Ti*w0)^2);    %modulus integral + plant
%Ta=(1/x/w0)
Ta=(x1/w0);      %PD's variable D
%K=Ca/(w0*Ta*sin(Fa*pi/180)+cos(Fa*pi/180))

K1=sqrt(1+(fa*x1)^2)/(sqrt(1+x1^2)); %modulus of pd

K2=Ca*K1 ;    %modulus Kp/I
Ks=K2*Ti;
control=tf(conv([K2*Ta K2],[Ti 1]),[Ta*fa 1 0])


%parallel version
nu=1+(1-fa)*Ta/Ti;
Kp=Ks*nu
Ip=nu*Ti
Dp=(((1/nu)-fa)*Ta)
N=(1/(nu*fa))-1

return
```

Appendix D: Plans

D.1 Cart assembly dimensioned (plan Nº1)

D.2 HVAC installation (plan Nº2)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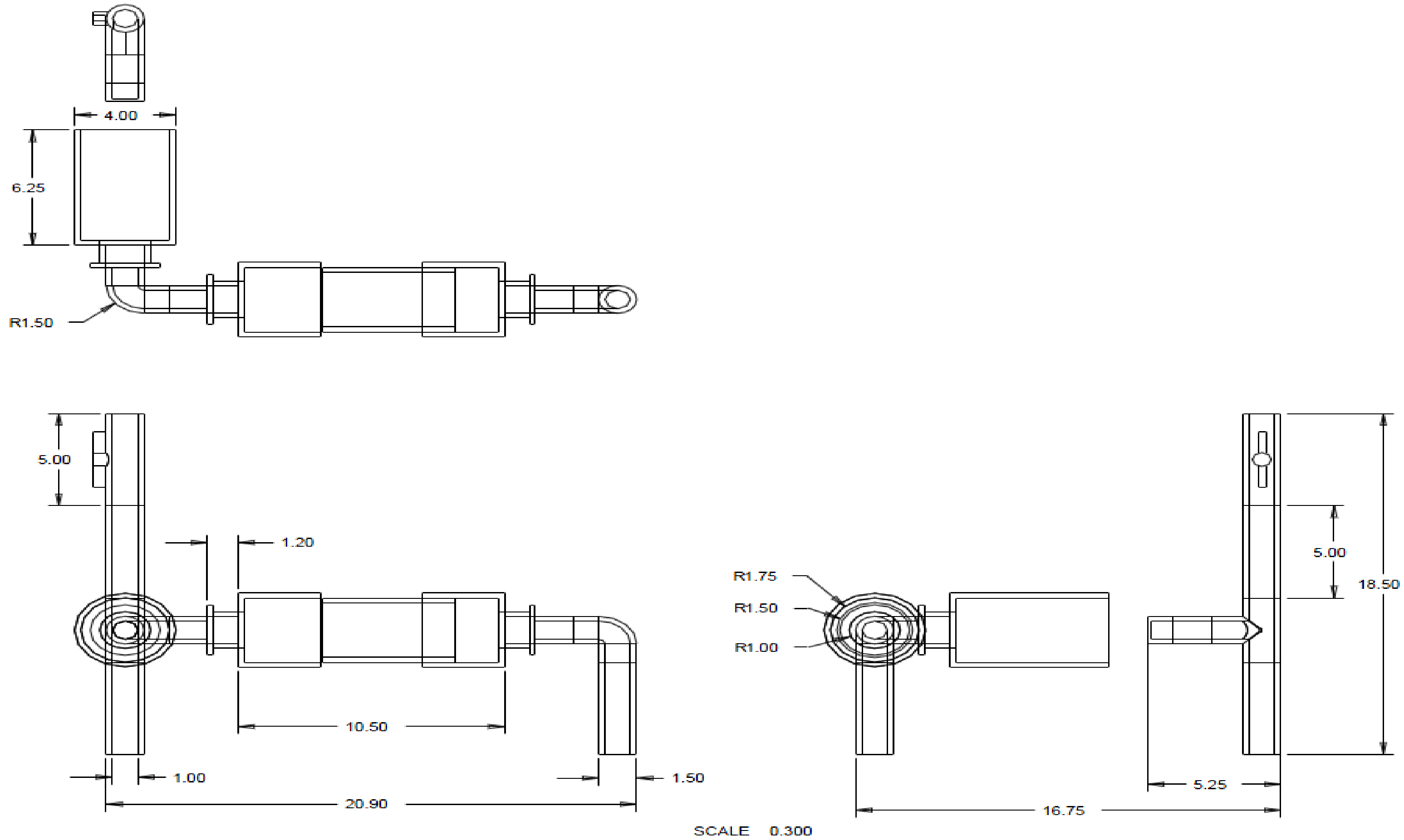
03-21-11
NAME: CART ASSEMBLY
AUTHOR: JAMES O'HARA
SCALE 0.090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5.00
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SCALE 0.300

UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

INGENIERO EN AUTOMÁTICA Y ELECTRÓNICA INDUSTRIAL

Design of a controlled HVAC system to implement in thermodynamics and controls laboratories.

David Morales Galán

Madrid, Junio de 2011